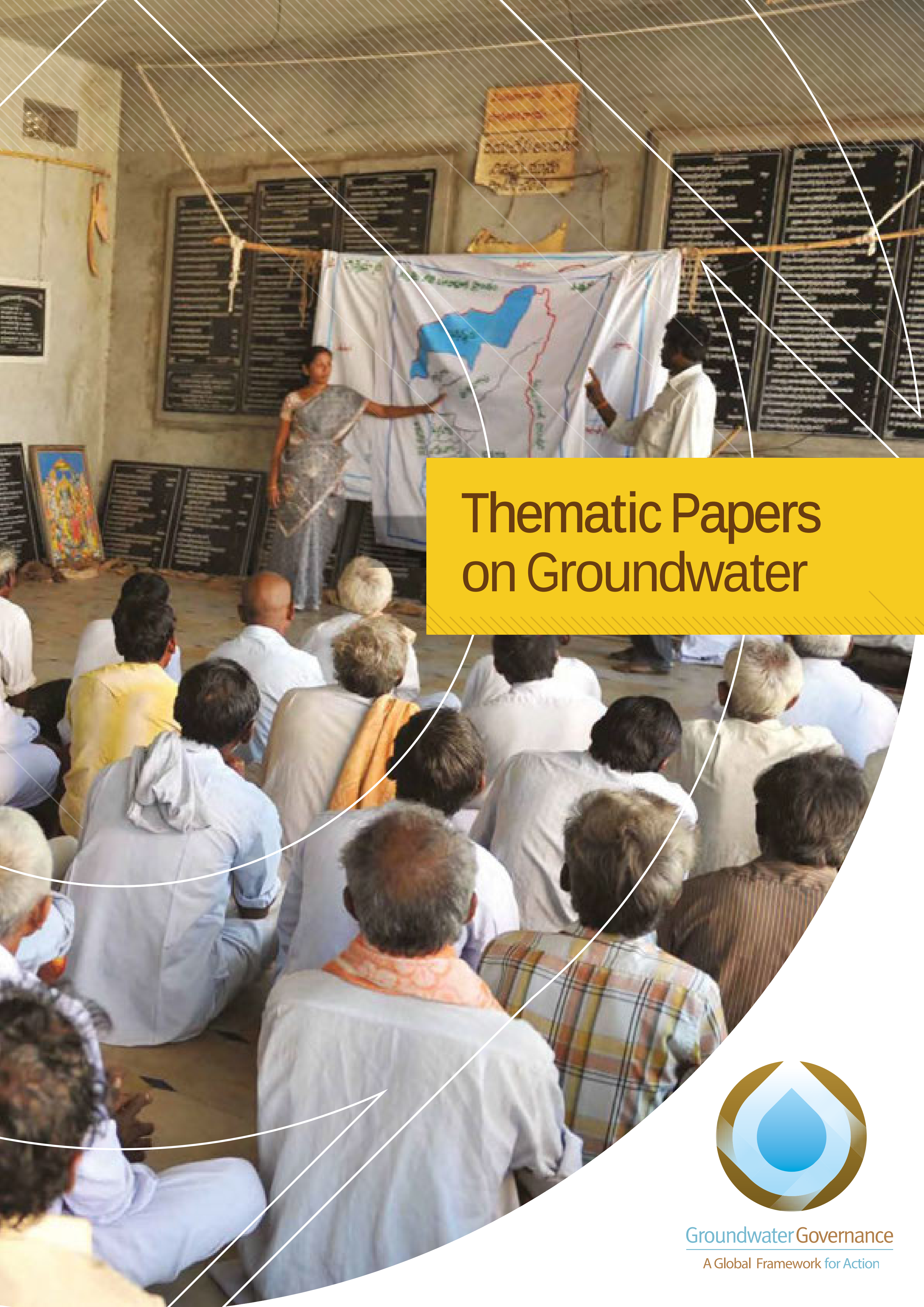

Thematic Papers on Groundwater

Groundwater Governance

A Global Framework for Action

Thematic Papers on Groundwater

April 2016

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Acknowledgements

The preparation of this collection of Thematic Papers compiling existing knowledge on different aspects of groundwater is the culmination of efforts by a large number of persons. Leading international scientists and experts drafted the papers and upgraded them more than once. Other experts, including participants to Regional Consultation Meetings, and members of the Project Steering Committee reviewed the drafts and provided insightful ideas, in addition to final proof-reading and editing. FAO information technology staff designed the final product. Sincere thanks and deep appreciation are extended to all.

This publication is one of the products of the Project "*Groundwater Governance – A Global Framework for Action*" implemented during the period April 2011- June 2016. The project was conceptualized by the World Bank and formulated under the leadership and supervision of Jacob Burke (FAO Officer at the time), in close consultation with partners. The project joint execution was led by FAO and overseen by a Steering Committee composed of Mohamed Bazza (Coordinator) and Nicoletta Forlano from FAO, Alice Aureli (UNESCO IHP), Shaminder Puri and John Chilton (IAH), Marcus Wijnen and Jacob Burke (World Bank) and Astrid Hillers (GEF).

Preface

This collection of Thematic Papers has been prepared during the first phase of the project *"Groundwater Governance – A Global Framework for Action"* (2011–2016). This project is a joint effort of the Global Environmental Facility (GEF), the Food and Agricultural Organization of the United Nations (FAO), UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrogeologists (IAH), the World Bank, and a multitude of scientists and water managers from across the globe. The project is an ambitious effort to raise global awareness on the urgent need for improved groundwater governance, to set the foundations for a global response to this new challenge, and to catalyse the necessary action.

The purpose of the Thematic Papers was to compile existing knowledge on groundwater governance in relation to contemporary development themes. This was seen a first step in achieving the project's objectives to support subsequent project activities. Among others, the papers were scheduled as an input to the project's five Regional Consultation Meetings that took place between April 2012 and March 2013, to prompt discussions on a broad range of aspects related to groundwater governance and to provide a suitable conceptual structure on groundwater development issues. To this extent it is hoped that the Thematic Papers contributed to achieving a broad agreement on the scientific and economic issues in relation to groundwater governance and to reaching consensus on the scope for future action.

By August 2011, a suggested general structure of the papers was defined (Baseline – Diagnostic – Prospects for governance) and ten selected themes had been identified that put a focus on different aspects and adopt different angles of view. Some of the themes deal with scientific-technical aspects (groundwater quality and quantity and approaches to their management), others with the governance and policy process in general or with selected aspects of groundwater governance (context, law, institutions, social and economic aspects). Leading international scientists and experts were subsequently invited to write the papers, and a first version of nine papers (TP1 through 8 and TP10) was available by the end of 2011 or beginning of 2012. In addition, two papers written already for the World Bank were added: TP11 on political economy (draft of 2009) and TP12 on climate change.

The project team in late 2012 distilled the core messages from the Thematic Papers and presented them in brief 'Digests' of three to four pages each, to facilitate next steps in the project implementation. Additionally, the project team elaborated a Synthesis Report which captures key messages from the Thematic Papers, paying particular attention to the interactions between the different thematic fields, to the main governance issues and constraints, and to the most significant prospects and recommendations for improving groundwater governance. The Synthesis Report does not present a summary of the Thematic Papers. Readers who want to access the information in full detail should consult these papers.

The Thematic Papers form together, along with their synthesis report and their digests, a unique volume of knowledge on groundwater governance related to development and environmental themes. The project made an effort to carry out a final editing of the papers and to make the information publicly available to those interested in the future direction of groundwater governance.

The Project Steering Committee

Rome, March 2016

Synthesis Report

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1. Introduction

People's initial attitude of taking groundwater - a fundamental natural resource and vital component of our environment - for granted and simply exploiting it according to individual demands had prevailed in most countries of the world until the mid-twentieth century. More recently, demographic pressures, economic and technological development and other factors have triggered unprecedented changes in the state of our groundwater systems, which has resulted in a growing awareness as to the finiteness and vulnerability of this critical resource.

In response to this new awareness, groundwater resources management (or groundwater management) has been embraced and developed in most countries. Usually initiated by governments, it pursues the controlled exploitation and adequate protection of groundwater to achieve broad society goals. Groundwater resources management comes in many forms and needs to be tailor-made to local conditions. It is action-oriented and uses technical instruments, legal and regulatory instruments, and incentives/disincentives to achieve its goals. While groundwater management is an inseparable part of overall water resources management, it deserves special attention due to the hidden, invisible nature of the resource, its high stock-to-flow ratio and the relatively dominant role of encouraging a change in behaviour as a tactic for achieving management goals. The common-pool resource characteristics of groundwater, the close interaction between groundwater and land use and the often-limited understanding among policy makers of its characteristics and of the geological processes that control its behaviour, are additional challenging features.

In spite of the efforts being made across the planet to introduce some degree of management to the use of this invaluable resource, groundwater exploitation at the global level is, however, far from being sustainable. Groundwater resources are being rapidly degraded in terms of quality and quantity, and the opportunities that currently exist for the *strategic* expansion of groundwater use are being compromised, or simply remain unknown to stakeholders. Effective management is often hampered by poor coordination and co-operation between relevant actors and/or by a lack of capable institutions and instruments, including technical, which can align stakeholder behaviour with policy objectives.

In view of this alarming situation, the concept of groundwater governance has (only recently) emerged. Groundwater governance can be qualified as "*an overarching framework and set of guiding principles that determines and enables the sustainable management of groundwater resources and the use of aquifers*". The lack of adequate governance – i.e. overarching enabling frameworks and guiding principles – hinders the achievement of groundwater resources management goals such as resource sustainability, water security, economic development, equitable access to benefits from water and conservation of ecosystems.

It is for these reasons that the Global Environmental Facility (GEF) has joined forces with the Food and Agriculture Organization of the United Nations (FAO), UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrogeologists (IAH), the World Bank, and a multitude of scientists and water managers from across the globe, in the project *"Groundwater Governance – A Global Framework for Action"*. The project represents an ambitious effort to raise global awareness on the urgent need for improved groundwater governance, set the foundations for a global response to this new challenge, and catalyse the necessary action.

This Synthesis Report highlights a number of key findings from the Project's first Component, which was designed to provide a science-based consolidation of knowledge of the groundwater resources economically exploitable under presently prevailing conditions, and their state (both quantity and quality), with focus on governance relevant aspects. As a part of this Component, twelve thematic papers have been prepared by leading international scientists and experts, most of them in 2011 or the first half of 2012; the corresponding titles and authors are listed in Box 1. Readers who want to access the information in full detail should consult these papers. This Synthesis does not present a summary of these papers, but distils from them key messages, paying particular attention to the interactions between the different thematic fields, to the main governance issues and constraints, and to the most significant prospects and recommendations for improving groundwater governance. It aims to contribute to achieving broad agreement on the scientific and economic issues in relation to groundwater and a consensus on the scope for future action.

Box 1: Thematic Papers

- No.1 – Trends in groundwater pollution: loss of groundwater quality and related services. *By Emilio Custodio*
- No.2 – Conjunctive use and management of groundwater and surface water within existing irrigation commands: the need for a new focus on an old paradigm. *By W.R. Evans, R. S. Evans & G.F. Holland*
- No.3 – Urban-rural tensions and opportunities for co-management. *By Ken Howard*
- No.4 – Management of aquifer recharge and discharge processes and aquifer storage equilibrium. *By Peter Dillon, Enrique Fernandez Escalante and Albert Tuinhof*
- No.5 – Groundwater policy and governance. *By Robert G. Varady, Frank van Weert, Sharon B. Megdal, Andrea Gerlak, Christine Abdalla Iskandar and Lily House-Peters. Major editing by Emily Dellinger McGovern.*
- No.6 – Legal and institutional frameworks. *By Kerstin Mechlem*
- No.7 – Trends in local groundwater management institutions. *By Marcus Moench, Himanshu Kulkarni and Jacob Burke*
- No.8 – Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction. *By M.J. Jones*
- No.9 – Macro-economic trends that influence demand for groundwater and related aquifer services. *By Jacob Burke (no full paper, only the brief 'digest' is available)*
- No.10 – Governance of the subsurface space and groundwater frontiers. *By Jac van der Gun, Andrea Merla, Michael Jones and Jacob Burke*
- No.11 – Managing the invisible: the governance and political economy of groundwater. *By Marcus Wijnen, Benedicte Augeard, Bradley Hiller, Christopher Ward and Patrick Huntjens*
- No.12 – Groundwater and climate change adaptation. *By Craig Clifton, Rick Evans, Suse Hayes, Ian Holman, Keith Westerhead, Steve Sagstad and Greg Hoxley*

2. Groundwater: facts and features

2.1 Some general characteristics of groundwater

Groundwater is present in pores and other open spaces inside the geological formations below the ground surface, in quantities much larger than any other liquid. Subsurface bodies of granular material or fissured rock capable of storing and transmitting significant volumes of groundwater are called *aquifers*. Aquifers thus are not only reservoirs, but also conduits for water. They are usually subject to replenishment (recharge) and outflow (discharge) that link them dynamically with the other components of the water cycle. Replenishment makes groundwater a renewable resource, characterized by stock (= the volume stored) and flow (=the flux maintained by recharge and discharge). The relatively high stock-to-flux ratio (compared to that of atmospheric water, surface water and soil moisture) explains the buffer capacity of groundwater.

There is an endless variation in groundwater systems around the world, mainly as a result of variations in geology and climate. As figure 2.1 shows, different climatic conditions may lead to very significant differences in groundwater state within geologically similar aquifer systems.

Groundwater represents almost 99% of all liquid freshwater on Earth, but its global flux is relatively small compared to that of other water cycle components. The rate of groundwater replenishment varies highly in time and in space. If an aquifer receives no or only insignificant quantities of recharge, due to geological or climatic conditions, then its groundwater is classified as 'non-renewable'.

Groundwater at such great depth that it has become isolated from the active water cycle is usually saline. Most of the groundwater at shallow and intermediate depth – the depths within reach of conventional water well drilling equipment – is fresh, however, and fit for common water use purposes. Only in some zones does the natural groundwater quality impose some restrictions, e.g. by a high degree of mineralization, or by high contents of arsenic or fluoride.

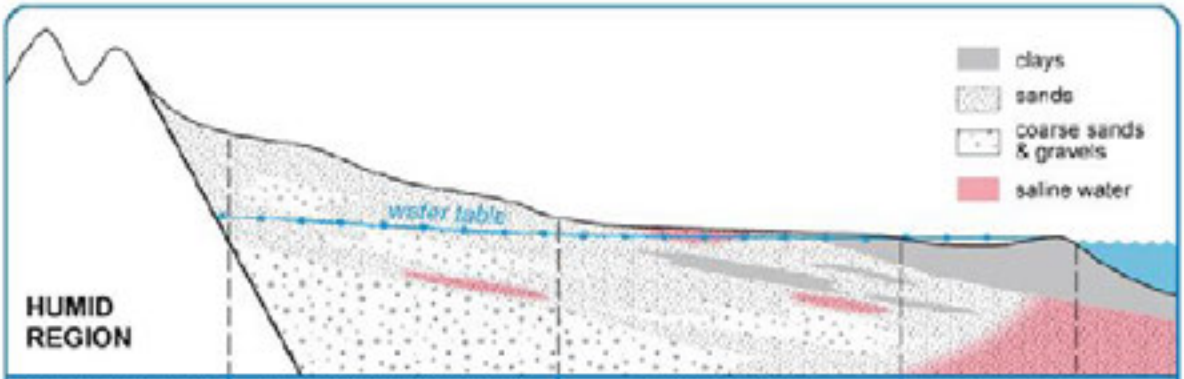
2.2 Early exploitation of groundwater

From time immemorial, people have exploited groundwater to satisfy their water demands. Initially, only shallow groundwater was accessible and no more than animal or human muscular power was available to abstract it. The abstraction works that have been developed in different parts of the world can be subdivided into two categories: gravity-based abstraction works (infiltration galleries, subsurface dams, spring capturing works, flowing wells) and abstraction works (mainly wells) that need an external energy source to lift groundwater to the surface. Several of these abstraction techniques were implemented by local communities rather than by individuals, either because the source was considered to be common property (e.g. a spring, or the subsurface flow inside small river beds) or due the project's size (like in the case of constructing, operating and maintaining qanats). In the case of wells, private ownership and community ownership have often developed in parallel.

The limited technology available before the twentieth century caused groundwater abstraction to remain modest in terms of volume, and thus usually without significant impact on local groundwater regimes or environments. In spite of the relatively low quantities abstracted, the importance of groundwater in ancient times should not be underestimated. It served and still serves vital needs, especially in areas where no other water sources are available year-round. The first recorded signs of governance arrangements are found in the arid and semi-arid zones, in the form of customary laws for groundwater access and use.

2.3 Groundwater withdrawal and use in modern times

Advances in drilling and pumping technology have strongly influenced the intensity and pattern of groundwater withdrawal and use worldwide. As a result, deeper aquifers can be tapped and higher rates of abstraction have become possible. The evolution of groundwater development and use has been different for different countries and varies among zones within these countries. Although other abstraction works still continue to function, pumped wells have become the most common tool for groundwater abstraction around the world.



ALLUVIAL SETTING	OUTWASH & PENE-PLAIN	FLOOD PLAIN	COASTAL PLAIN
Hydrogeological Conditions	unconfined high-yielding aquifer with increasingly deep water table but rapid vertical recharge	multi-layered aquifer with shallow water table and moderate waterwell yields but with some 'rejected recharge'	confined aquifer with very restricted vertical recharge and reducing effective thickness
Water Resource Management Implications as in Humid Regions	much care needed to avoid 'double-accounting' due to infiltration of surface water via irrigation systems	poorly-managed surface water irrigation results in soil water-logging/salinisation; river baseflows used for irrigation can be greatly reduced by 'upstream' consumptive groundwater irrigation use	aquifer highly vulnerable to saline water intrusion on intensive exploitation and reversal of natural hydraulic gradients
Water Resource Management Implications as in Hyper-Arid Regions	high soil-profile salinity under natural vegetation mobilised when irrigated cultivation introduced	groundwater at depth naturally saline with freshwater restricted to lenses beneath major rivers/irrigation systems	surficial aquitard may also contain saline water which can seep downward

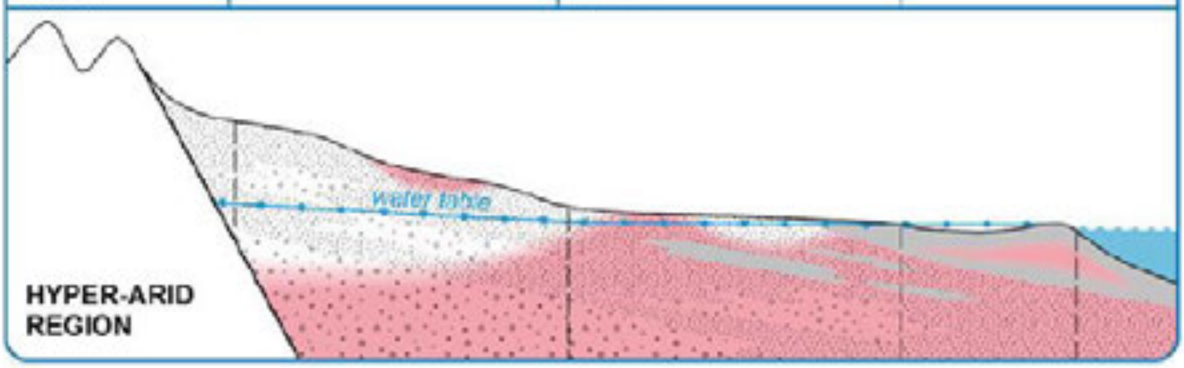


Figure 2.1 Schematic profile of a typical alluvial groundwater system located between mountains and sea, for two different climatic settings, detailing the variation in groundwater surface water connectivity and salinization hazards (Evans et al., Thematic Paper 2; after Foster et al., 2011).

For centuries, hand pumps had been used to supply domestic water to communities or individual households, and they continue to play an important role in rural water supply in developing countries. In order to satisfy criteria set during the International Drinking Water and Sanitation Decade (IDWSSD, 1981 – 1990) hand pumps should be robust, affordable and easily maintainable. These criteria are not always met and this has resulted in many failures. The Village Level Operation and Maintenance (VLOM) concept, introduced during the 1980s, initially focused on hardware only, but this was later expanded to also include the management aspects of maintenance, such as community decisions on when to service and by whom, and how to pay for the cost of repairs.

Today, groundwater pumping for urban water supply makes use of energised rotodynamic pumps and metropolitan centres have access to the latest technologies. Robust diesel and electric powered pumps have also enabled an exponential growth of groundwater-irrigated agriculture, and energy costs therefore make up a large part of total cost for groundwater. While urban water supply is a collective provision (although often in the hands of private companies), most of the groundwater for irrigation is abstracted by private farmers on an individual basis. Rather than being seen as a public good, there exists a widely entrenched perception that groundwater belongs to the owner of the land where it is withdrawn.

Globally aggregated groundwater abstraction has increased approximately six-fold during the last 50 years and is estimated to have reached a rate of 986 km^3/year in 2010. Figure 2.2 shows the observed trends in nine countries with intensive groundwater exploitation.

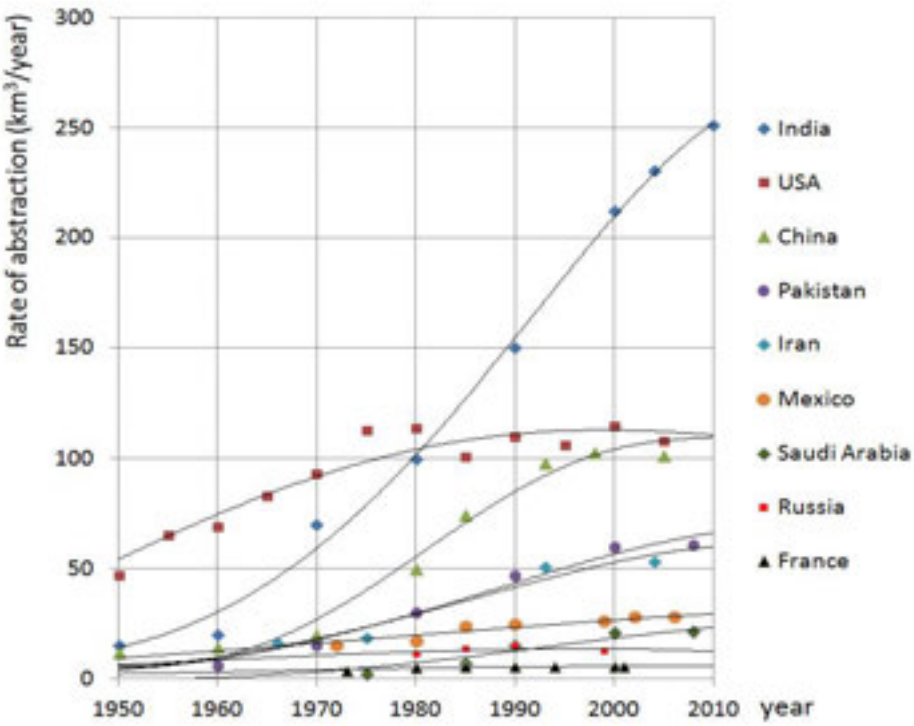


Figure 2.2 Evolution of groundwater abstraction in selected countries, period 1950-2010 (Custodio, E., Thematic Paper 1; after Margat and Van der Gun, 2013).

Figure 2.3 illustrates the global variation of groundwater abstraction intensity, expressed in mm/year (1 mm/year = 1000 m^3/year per km^2). The three countries with the largest national groundwater abstraction are India, USA and China, which are also the three countries with largest area of groundwater-irrigated agriculture. The sum of their withdrawals is equivalent to 48% of the global total. Globally, approximately 70% of all abstracted groundwater is used for irrigation, 21% for domestic purposes and 9% for industrial water. The share of groundwater in total global freshwater abstraction is 26%, but this share varies widely between countries (and smaller spatial units) and between the main water use sectors.

These numbers and percentages are illustrative of the huge importance of groundwater as an extractable resource. The percentages would be even higher still if they represented not the volume abstracted, but the added value of the abstracted water as an indicator of the relative importance of groundwater. This is due to the fact that groundwater is almost always more reliable than surface water, greatly reducing the risk of unforeseen water shortages.

As far as is known, the aggregate economic contribution of groundwater to national economic development has been estimated in only a few cases. For instance, the Planning Commission of India has estimated that groundwater used for agriculture makes a 9% contribution to the country's GDP. This is an under-estimate of the total contribution of groundwater because the array of urban, municipal and industrial water supplies from India's aquifers have not been factored into the estimate. The International Water Management Institute (IWMI) estimated the world's groundwater-irrigated agriculture to have a value of USD 150 to 170 billion at the beginning of the 21st century.

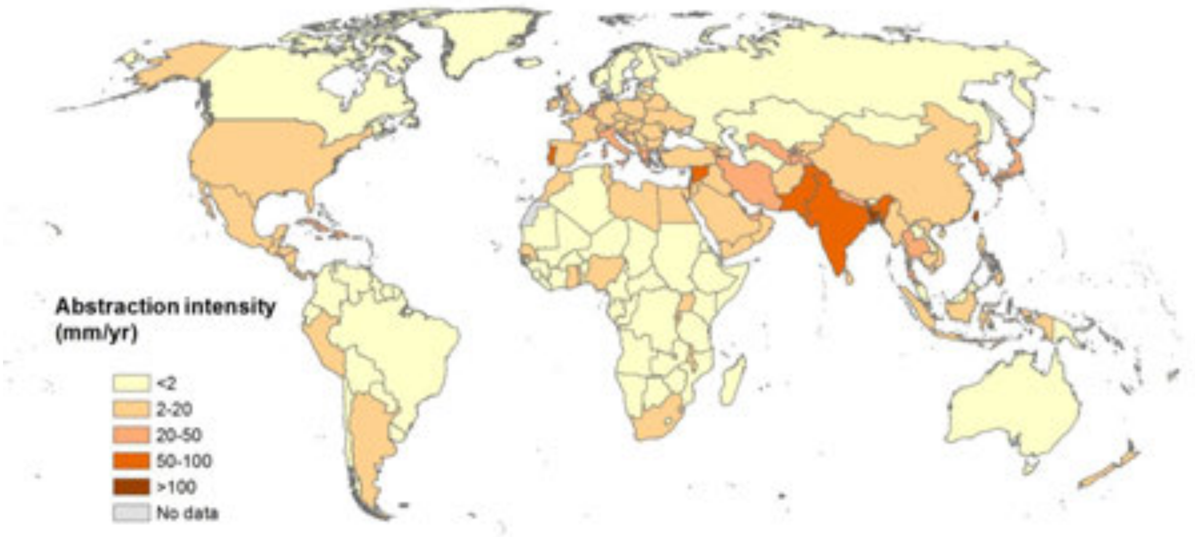


Figure 2.3 Intensity of groundwater abstraction by country for the year 2010, in mm/year (After Margat and Van der Gun (2013), estimated on the basis of statistics in global databases).

In addition to the main categories of groundwater use (domestic water supply, irrigation and industrial water), several other uses deserve mentioning. The first is the use of groundwater in thermal baths or spas, undeniably important for therapeutic or touristic purposes, however the quantities of water involved are comparatively low. A related use is mineral water, originally consumed at the source (at spas or springs) but nowadays mostly distributed as bottled water (like ordinary bottled water that does not qualify as 'mineral water') and likely included in the statistics on industrial water. Groundwater is also used for the exploitation of geothermal energy and for seasonal subsurface heat storage and recovery. In both types of use the pumped groundwater is usually re-injected, resulting in low levels of consumption. Globally, only a small portion of the available high-temperature groundwater resources suitable for electricity generation (the so-called *high enthalpy* geothermal resources) are exploited, while the direct use of the huge amount of natural heat contained under normal gradient[1] conditions (*low enthalpy* geothermal resources) are being developed very slowly. Thus, there is scope for significant expansion of these groundwater uses in the future.

2.4 Development of non-renewable groundwater resources

Most groundwater resources currently being exploited are renewable, which implies that in principle they offer the possibility for sustainable use. This means that if exploited with sufficient care and control, the aquifers will remain in a long-term dynamic equilibrium, i.e. the volume stored and the groundwater levels will remain stable. Some aquifers face less favourable conditions (be it by geological or by dry climatic conditions) and receive no or only insignificant replenishment, meaning their groundwater is classified as 'non-renewable'. Withdrawing groundwater from non-renewable resources will necessarily lead to steady depletion of the volumes of groundwater and thus require special exploitation strategies that differ from those adopted for renewable groundwater resources. Such strategies will have to consider explicitly the finiteness of the exploitable resources, indicate to what extent the benefits of present-day groundwater use may contribute to future wealth, and include an 'exit strategy', i.e. a clear idea on the sources of water to be tapped for basic needs after the non-renewable groundwater resource will have been exhausted.

2.5 Artificial groundwater discharge by drainage

Withdrawal for water use is not the only way in which humans actively interfere in groundwater regimes. In some parts of the world there is a long tradition of draining shallow-water table zones in order to prevent water-logging and make the land suitable for intended land use purposes. In such cases, the water pumped or drained by gravity is only a by-product of the activity and is usually dumped (without being used). Around 167 million hectares of artificially drained land have been identified around the world, but how much groundwater is discharged in this

[1] 25 °C per km of depth.

way is not yet known. Typical examples are the low-lying polder areas of The Netherlands and the Nile delta in Egypt. Similar activities include the drainage intended to facilitate mining and various types of use of the subsurface, as well as temporary drainage of building pits. Again, the volumes of groundwater pumped annually in this way are not known.

2.6 Ecological and environmental functions of groundwater

Groundwater is not only relevant as an extractable resource. In many zones it is also indispensible for, or at least contributes to, sustainability of surrounding ecosystems. Groundwater maintains the permanent or seasonal baseflow of streams, feeds springs, supports ecosystems and shallow-water table agriculture and can play a role in maintaining the stability of the land surface. Valuing these groundwater functions in economic terms is very difficult and inherently subjective. In many countries there is a steadily growing awareness of the value of these functions of groundwater and this awareness tends to grow in tandem with broader economic development. These ecological and environmental functions are often negatively affected by groundwater withdrawal.

2.7 Groundwater and land use

Groundwater and land use are strongly interconnected. On the one hand, the presence of groundwater and its quantity and quality may have a significant impact on the land use, in particular if the land is used for agricultural purposes dependent on specific water- table conditions or requiring irrigation. On the other hand, the type of land use and the adopted land use practices may have a profound impact on the groundwater regime (e.g. on groundwater recharge) and in particular on the groundwater quality. Many near-surface aquifers around the world are exposed to pollution and most sources of groundwater pollution are related to land use practices. The application of manure, fertilizers and pesticides in agriculture is a primary source of groundwater pollution, in addition to many other sources such as leaking sewerage systems, accidental spills of contaminants, waste dumps and wastewater discharge.

2.8 Groundwater withdrawal and other uses of the subsurface space and its resources

Groundwater is only one of the interests of mankind in the subsurface. Mining activities also have a very long tradition and are expanding in many parts of the world, targeting a large variety of valuable solid materials (like metals and minerals), and more recently also energy (oil, gas and geothermal energy). But the subsurface is also increasingly in use for other purposes. At shallow depth, this includes the construction of pipelines, sewerage systems, cables, tunnels, subways, underground car parks and subsurface parts of buildings. Various geological formations at greater depths are judged to be an attractive option for the disposal of hazardous waste (e.g. nuclear or hydrocarbon waste) and for injection and recovery purposes, such as carbon capture and sequestration (CCS).

2.9 Groundwater and its many interdependencies

It is clear that groundwater is not an isolated resource. It is subject to many interdependencies. It interacts with other components of the hydrological cycle (see e.g. Figure 2.4), but is also involved in other natural cycles such as the geochemical cycle and the global carbon cycle. It is affected by climate variability and climate change and it interacts with numerous ecosystems. The state of groundwater is influenced by many human activities, above and under the land surface, and in turn groundwater abstraction affects all of these activities. Groundwater plays an important role in livelihoods and economies, and these socio-economic conditions, in turn, produce feedback to the state of the groundwater systems. Understanding groundwater and how it varies over time requires an appreciation of these complex resource interdependencies.

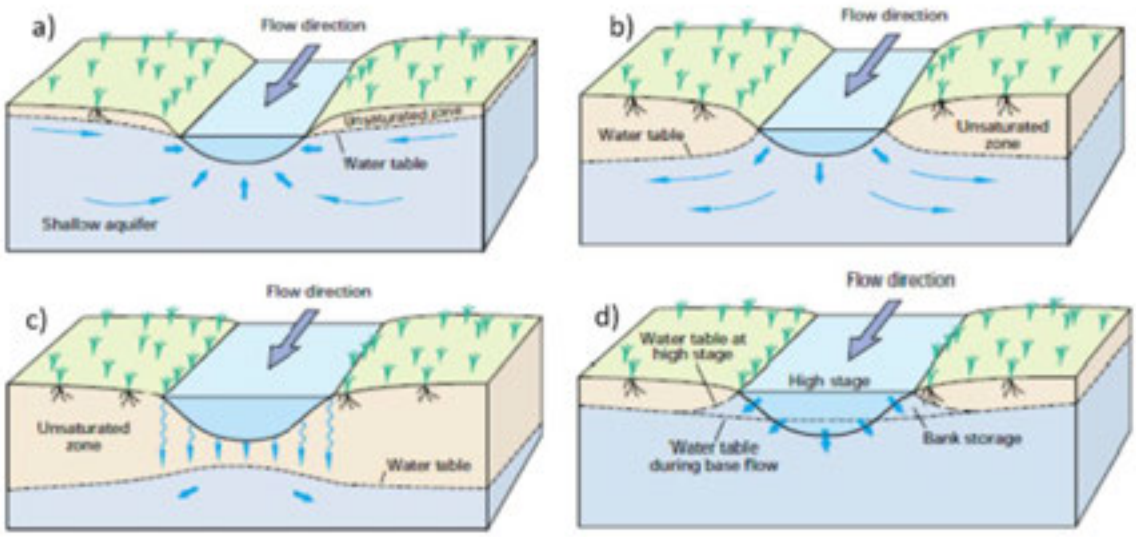


Figure 2.4 Connectivity relationships between groundwater and streams: a) gaining connected system; b) losing connected system; c) disconnected system; d) fluctuating connected/disconnected system (Evans et al., Thematic Paper 2; modified after Winter et al., 1998).

3. Groundwater resources management and groundwater governance

3.1 The need to organize an orderly path

As outlined previously, groundwater plays an important role in daily life. It is essential for meeting vital water demands of numerous people and ecosystems and for the socio-economic development of most areas in the world. It is immediately obvious that ensuring the sustainability of this role is of crucial importance. Nevertheless, a strong and steadily increasing interaction between individuals and groundwater systems is observed and the cumulative effects of individual action and behaviour usually do not result in socially optimal situations. On the contrary, individuals tend to act solely in their own short-term interests, which often diverges significantly from the long-term interest of the wider community that he or she belongs to. As a result, actions of individuals may produce negative impacts on communities, other individuals, the resource base or the environment (externalities). Individuals are often not aware of these impacts, or they give no priority to preventing them, partly because the common-pool resource nature of groundwater is a complicating factor. In addition, there are also external factors (like climate change and population growth) that generate changes in groundwater conditions and may cause problems that are beyond control of individuals. Driven by their collective responsibility, many communities or governments feel the need to respond to these problems and to organize an orderly path. These responses fall within the domains of groundwater resources management and groundwater governance.

3.2 Groundwater resources management and governance - and how they differ from each other

Groundwater resources management and groundwater governance are closely related. They come into being when societies realise that actual conditions urge that human efforts related to groundwater should go beyond mere exploitation.

Groundwater resources management was the first of the two paradigms to be adopted, and this happened at different times in different countries. It can be defined as follows:

> *Groundwater resources management is a planned and ongoing activity to optimize the exploitation and use of local, regional or national groundwater resources, taking into account the sustainability of the groundwater resources and of the groundwater-related environment and ecosystems.*

Groundwater resources management is action-oriented and the operational instruments used include technical interventions, legally enforceable regulations and positive or negative incentives. The latter two categories aim at influencing human behaviour, which is the cornerstone of groundwater resources management and governance. Compared with situations of mere groundwater exploitation without any coordination or precaution, groundwater resources management integrates all water users and water use sectors and introduces a 'resource custodian', often the government, who is in charge of preventing degradation of the groundwater resources due to pollution or overexploitation. In addition to these objectives of maintaining resource sustainability and maximizing economic profit, groundwater resources management often aims to improve access to groundwater, for spreading the benefits of groundwater more equitably and for protecting the ecological and environmental functions of groundwater. In many countries, groundwater resources management has gradually evolved from an isolated or stand-alone activity into a component of integrated water resources management (IWRM), involving close coordination with the management of surface water, land use and the environment.

There is diversity of opinions on the effectiveness of groundwater resources management in practice. While there are some examples of successes, there is also ample evidence that in many cases groundwater management fails to meet set objectives. This can be attributed to a range of factors including the inherent complexity of the groundwater setting, limited awareness and information, low levels of political commitment, groundwater being undervalued, flaws in legislation, weak institutions, inadequate financing, lack of co-ordination and stakeholder involvement, etc. The dominant opinion is that ineffective governance is the main bottleneck to successful groundwater resources management.

Governance is a complex concept, which is reflected in the fuzzy and often rather long definitions produced by a variety of authors. A comparatively concise definition of governance is presented by Wijnen *et al.* (2012):

> *Governance is understood as the operation of rules, instruments and organizations that can align stakeholder behaviour and actual outcomes with policy objectives.*

Sanier and Meganck (2007) provide the following definition of groundwater governance:

> *Groundwater governance is the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global.*

The specific elements mentioned in this second definition (responsibility, participation, etc.) are value-laden terms that define '*good* governance' as opposed to just 'governance'. These qualities may be the views and preferences of some actors, but not necessarily all.

According to Foster and Garduño (2013), the term 'governance' is generally understood to mean the exercise of political, economic and administrative authority of national affairs at all levels – and comprises the mechanisms, processes and institutions through which citizens articulate their interests, mediate their differences and fulfil their legal rights and obligations. Consequently, they conclude that:

> *Groundwater governance comprises the promotion of responsible collective action to ensure socially-sustainable utilisation and effective protection of groundwater resources for the benefit of humankind and dependent ecosystems.*

In spite of some room for differences in interpretation of these definitions, it may be concluded that they characterise groundwater governance as being process-oriented rather than action-oriented.
Even within the groundwater community there is some confusion on the difference between the concepts 'groundwater resources management' and 'groundwater governance'. This has resulted in the two terms being used both inconsistently and interchangeably (see Box 2).

Box 2: Groundwater governance or groundwater resources management?

It is difficult to draw a sharp and clear line between 'groundwater resources management' and 'groundwater governance'. With some degree of simplification one might say that (ground)water management focuses on "what is being done", while the local, regional or national government frameworks define "who participates" in formulating strategies and in implementing them, and "how the different actors interact". However, the differentiation between the two concepts in practice may partly depend on the different views, perceptions and jargon between the pioneers of groundwater resources management (mainly engineers and hydrogeologists) and those of groundwater governance (social scientists). This seems to be in line with social scientists describing groundwater governance as "an overarching framework and set of guiding principles that determines and enables the management of groundwater resources and the use of aquifers", while hydrogeologists and engineers rather look upon groundwater governance aspects as the "enabling environment" of groundwater resources management. In reports and publications on groundwater governance one may find issues discussed that according to what is outlined above primarily belong to the domain of groundwater resources management, and vice versa.

3.3 Principles of good groundwater governance

General principles of good groundwater governance – like the governance of all other natural resources – are included in the above-mentioned definition by Sanier and Meganck: the application of responsibility, participation, information availability, transparency, custom and rule of law.

A number of important aspects and considerations in this context, subdivided into four categories, are listed in Table 3.1. These aspects give an impression of the variety of elements and dimensions attributable to groundwater governance.

Table 3.1 Important aspects to be considered in groundwater governance (Varady et al., Thematic Paper 5)

Political and institutional	**Socio-cultural**	**Economic**	**Ecological**
Accountability Representation Consistency Scalar match Institutional match Institutional capacity to adapt to change and uncertainty	Perceptions about groundwater Religious and spiritual traditions Social learning Social inclusion Ethics Multi-level/ multi-scale/polycentric governance models	Imperfection of price signals (market failures) Role of water scarcity and groundwater storage Water quality impacts Inadequate water use monitoring Role of private sector Role of public-private partnerships Ability to pay External costs	Diffusivity and conduciveness Attenuation rates Renewability Vulnerability Provisioning versus ecosystem services

As groundwater is a 'common-pool resource', groundwater governance is likely to benefit from an application of the principles defined by Elinor Ostrom for developing institutional arrangements for the management of such resources (Foster and Garduño, 2013):

- Clearly defined boundaries for resource evaluation and allocation
- Congruence between proposed resource allocation and prevailing natural constraints
- Formal recognition of the rights of the local communities to organize resource use
- Collective arrangements for the participation of stakeholders in decision-making
- Nested stakeholder groups to cope with geographically large resource systems
- Effective independent monitoring of resource status
- Graduated sanctions on resource users or polluters who do not respect community rules
- Mechanisms for conflict-resolution that are accessible, rapid and inexpensive.

There are no generally valid blueprints for dealing with all these aspects or applying all the aforementioned 'good governance principles'. As Elinor Ostrom wrote: "context matters". This implies that the adoption of widely embraced 'good governance' paradigms such as sustainability, market approaches and decentralisation need to be critically viewed in the particular context of each case.

Finally, it needs to be emphasized that 'good governance' and 'effective governance' are two different concepts. Groundwater governance is effective if the goals set out by the government are being met. Governance is good if countries attempt to reach these goals in a way that incorporates 'good governance principles' as outlined above.

4. Observed trends and other factors challenging groundwater governance

4.1 Groundwater state and observed trends in state

Groundwater quantity and quality are major determinants of how much groundwater can be withdrawn at a certain location and for which purposes it can be used. Under natural conditions, the long-term averages of these state variables tend to be stable. Human influences, however, have caused changes in the groundwater state (quantity and/or quality) in many locations, often in the form of a trend over time and usually making groundwater less attractive for withdrawal.

Groundwater quantity refers to a number of interlinked groundwater variables: groundwater level, stored volume, recharge, flow and discharge. Together they constitute the groundwater regime and the corresponding numerical values define the groundwater budget. From the point of view of withdrawal, relatively shallow groundwater levels are preferred, because the cost of abstracted groundwater (including the cost of infrastructure, energy and other operation and management components) increases with greater depth. The volume of groundwater stored is decisive for the buffer capacity of the groundwater system, which keeps groundwater available during dry periods without any recharge events. Such dry periods may vary from several months for groundwater systems with a small volume stored to many thousands of years for aquifers with huge reserves. Natural groundwater discharge is not a loss, but is often essential for maintaining ecosystems and the baseflow of streams.

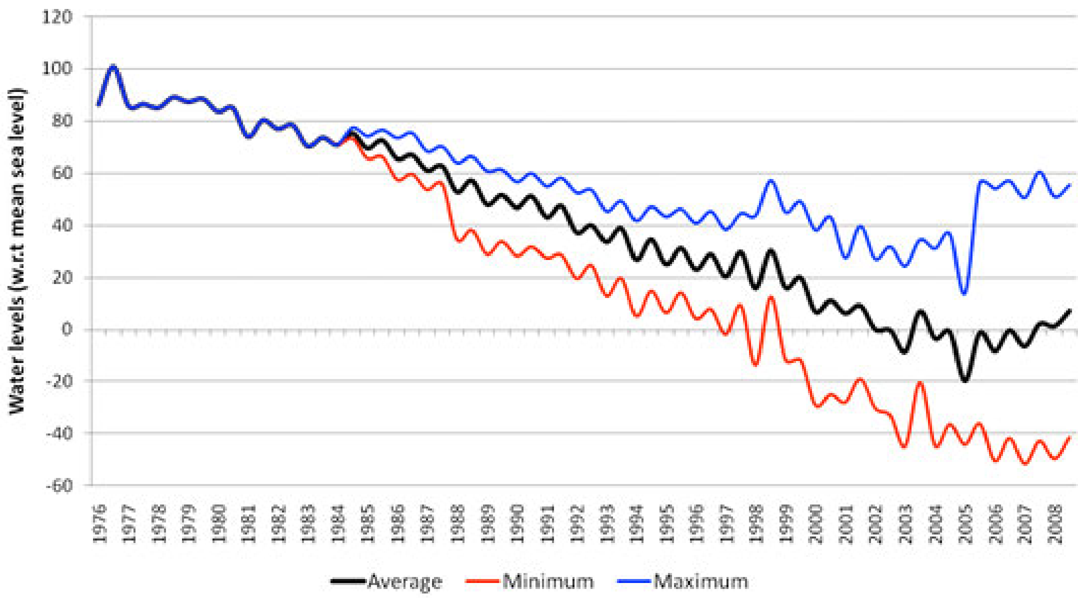


Figure 4.1 Declining groundwater levels in the Kukarwada sub-district, Mehsana region, Gujarat, India (Jones, Thematic Paper 8. Source: http://water.columbia.edu/research-projects/india/gujarat-india/).

Anthropogenic changes in the two connected groundwater quantity state variables – groundwater level and groundwater storage – are observed in many parts of the world. Most frequently these changes consist of declining groundwater levels (illustrated in Figure 4.1) and an associated reduction of the stored groundwater volume (groundwater depletion), caused by intensive groundwater abstraction, drainage or land use practices, and increasing impermeabilisation of the land surface. The root causes of these pressures, in turn, are demographic factors (population growth and urbanization), economic development and technological innovation that lead to steadily growing water demands (see below) and to modification of groundwater recharge rates. Climate change is expected to aggravate the pressures in many parts of the world, in particular in the arid and semi-arid zones, where water demands tend to increase under simultaneously decreasing groundwater recharge rates (see Table 4.1).

Table 4.1 Summary of climate change impacts on recharge under different climatic conditions (Clifton et al., Thematic Paper 12)

High latitude regions	Temperate regions	Arid and semi-arid regions
Recharge may occur earlier due to warmer winter temperatures, shifting the spring melt from spring toward winter.In areas where permafrost thaws due to increased temperatures, increased recharge is likely to occur	Changes to annual recharge will vary depending on climate and other local conditions. In some cases little change may be observed in annual recharge, however the difference between summer and winter recharge may increase	In many already water stressed arid and semi arid areas, groundwater recharge is likely to decrease.However where heavy rainfalls and floods are major sources of recharge, an increase in recharge may be expected. E.g., alluvial aquifers where recharge occurs via stream channels, or bedrock aquifers where recharge occurs via direct infiltration of rainfall through fractures or dissolution channels.

Source: Holman et al, 2001; Döll and Florke, 2005; van Vliet, 2007; Dragoni and Sukhija, 2008.

Global groundwater depletion was still insignificant until 1950, but since then it has increased rapidly (see Figure 4.2) and currently adds up to around 145 km^3/year (Margat and Van der Gun, 2013). This not only affects the water resource conditions on the continents, but is also contributing to an increase of the volume of water stored in the oceans (sea level rise). Long-year trends of groundwater level rise are also observed in certain areas, but the total area concerned is much smaller than that of groundwater depletion and problems can be solved relatively easily by technical measures.

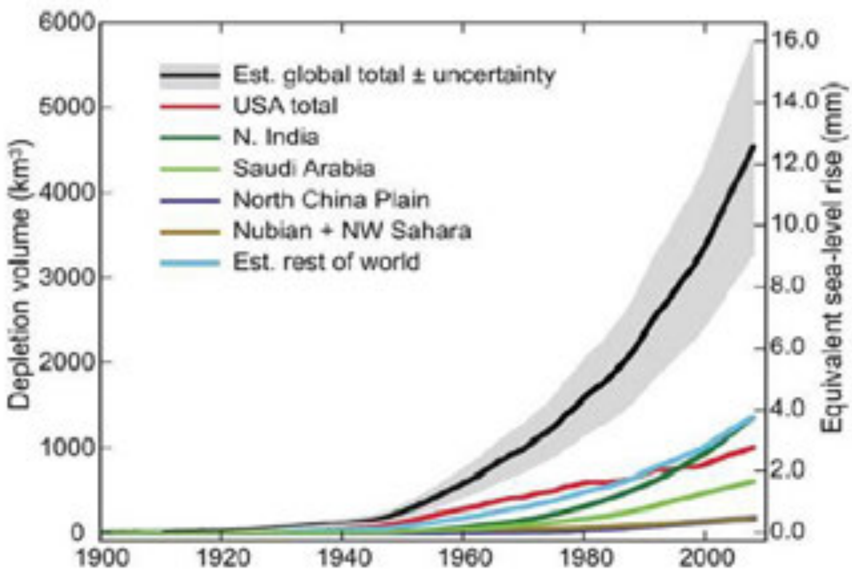


Figure 4.2 Estimated cumulative global depletion, period 1900-2008 (Dillon et al., Thematic Paper 4; after Konikow, 2011).

The impacts of groundwater depletion include higher cost of abstracted groundwater; reduction of well yields, spring discharges and baseflows; degeneration of ecosystems; reduction of the yields of phreatophytic agriculture; land subsidence; reduction of the groundwater buffer (smaller potential bridging periods); inflow or migration of saline or brackish water into the aquifer; reduction of the yield of infiltration galleries; springs falling dry and permanent loss of artesian conditions; a contribution to sea level rise; and in extreme cases the loss of an exploitable groundwater resource.

Groundwater quality is a complex concept as it depends on the physical properties of groundwater, its bacteriological content and in particular the large number of dissolved constituents that define its chemical composition. Groundwater abstracted from the upper few hundred metres below the ground surface is usually of a good natural quality, meaning that it is suitable for most domestic, agricultural and industrial uses. At this depth there are only a limited number of areas worldwide that contain groundwater that is saline or brackish in its natural state, or characterised by excessive concentrations of certain components such as arsenic or fluoride.

Human activities are also affecting groundwater quality. An example is the intrusion of seawater into a coastal aquifer triggered by groundwater abstraction, as illustrated in Figure 4.3. However, quality degradation is more widespread by the influx of many types of pollutants produced by humans. Zones with growing pollution trends can be found in virtually every country. The sources of pollution are manifold: domestic and industrial waste and wastewater; animal husbandry and its waste products; manure, fertilizers and pesticides used in agriculture; irrigation water; landfills and subsurface waste deposits; leaking tanks; accidental spills, etc. Pollutants may degrade in the subsurface to some extent, but often they simply appear in the aquifers after a period of delay. These delays, and the large spatial dimensions of aquifers, mean that the pollution trends of groundwater often are detected late. This is a serious handicap for aquifer protection efforts. Phreatic aquifers with shallow water tables are particularly vulnerable to pollution. High population densities, poor sanitary conditions and intensive agriculture and industry contribute to the pollution risk. Figure 4.4 gives an impression of the complexity of groundwater pollution in urban environments. Pollution is a virtually irreversible and continuing phenomenon worldwide.

The impacts of groundwater pollution are often severe. Minor pollution makes groundwater unsuitable for uses that are sensitive for quality, in particular for domestic water use. If significant pollution occurs, in terms of type and concentration of pollutants present in groundwater, then in practice it usually means that an exploitable groundwater resource is lost.

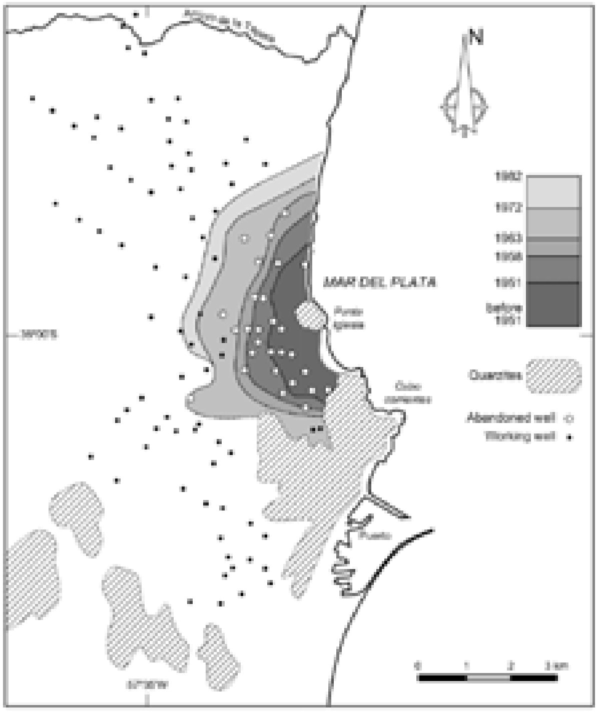


Figure 4.3 Salinity advancement in groundwater in the Mar del Plata urban area (Argentina), due to local intensive pumping (Custodio, Thematic Paper 1; after Bocanegra et al, 1992).

4.2 Groundwater demand

Groundwater demand should be seen in the context of total water demand. In principle, most water demands can be satisfied by any source of fresh water, be it surface water, groundwater or any other source, including non-conventional sources such as desalinised seawater. Whether to opt for groundwater or for another source depends on the availability and capacity of the different sources and on the comparative attractiveness of groundwater. For instance, in arid and semi-arid regions groundwater is often the only source that can supply water throughout the year, and it is therefore indispensable for satisfying dry-season water demands. In addition, groundwater is often preferred because of its predictable good quality or because it can be withdrawn close to where it is or will be used. On the other hand, surface water may be less expensive and thus a preferred source for irrigation in the floodplains along numerous permanent rivers around the world.

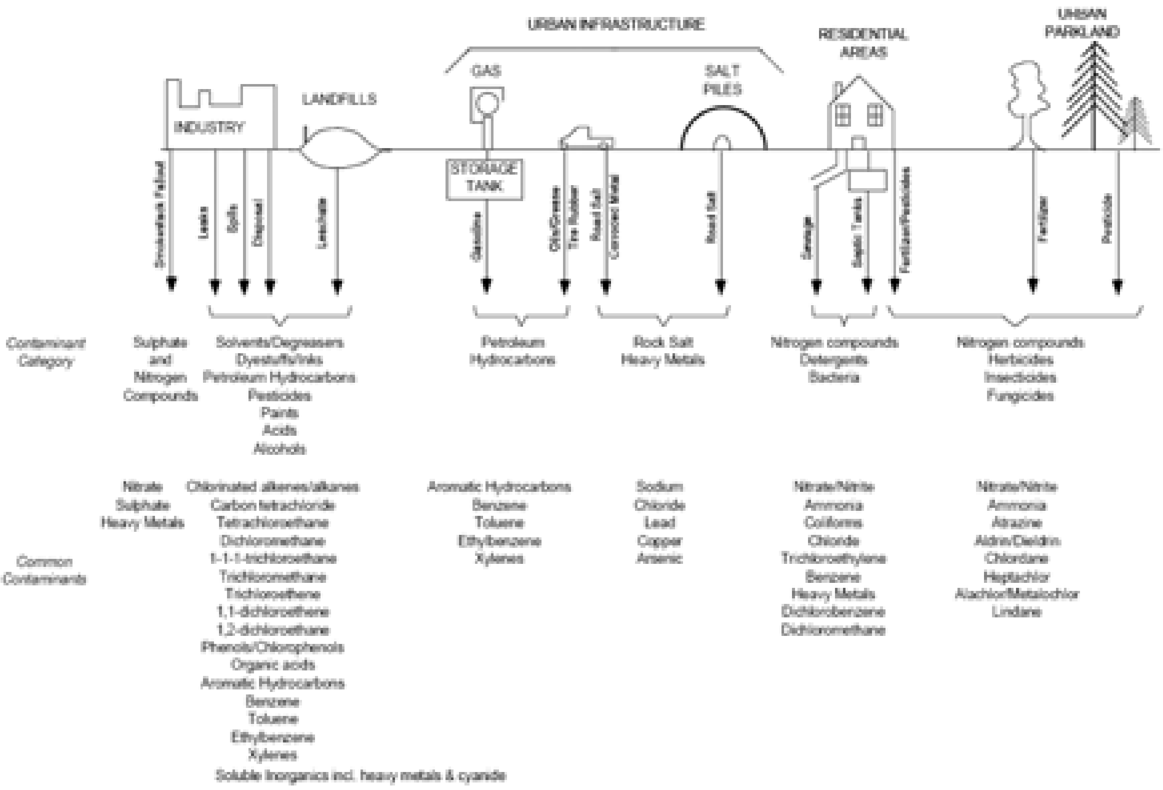


Figure 4.4 Sources of groundwater contamination in urban areas (Howard, Thematic Paper 3).

In general, water demands are increasing continuously over time, and this includes demand for groundwater. A major driver behind this increase is population growth, followed by economic development (including the expansion of the irrigated acreage), urbanisation and the ambition to significantly improve water supply and sanitation facilities in those parts of the world where these are currently inadequate (as stipulated in the Millennium Development Goals). While global population has approximately doubled during the period 1960-2000, total global groundwater withdrawal has more than tripled during the same period. Annual rates of growth of groundwater withdrawal are still high in several Asian countries (3% or more), but withdrawals have stabilized or are even slightly decreasing in most of the industrialized countries of Europe, North America and Australia. It will be clear that increasing groundwater withdrawals lead to increasingly stressed groundwater systems, because the quantity of the exploitable groundwater resource – subject to artificial recharge, but also to depletion and quality degradation and changes in recharge – is at best more or less constant.

It is not easy to analyse how macro-economic trends affect the demand for groundwater. The macro-economic conditions under which many private decisions to pump groundwater or pollute aquifers are taken may have little impact where (and when) demand is inelastic due to the absence of an alternative source of water or an alternative means of disposal. In addition, while agricultural groundwater supply may be highly elastic with respect to commodity price signals, evidence points to highly inelastic demand for groundwater when input subsidies for energy are removed or fuel taxes imposed.

4.3 Perceptions and public behaviour

The general public is usually largely uninformed about the groundwater in their local area. This means that in general the public have no knowledge about the invisible groundwater stored below their feet, nor do they understand groundwater recharge, flow and natural discharge. The majority of those who dump waste and wastewater on the surface or apply fertilizers and pesticides to their crops are not aware that these practices may pollute the groundwater resources. Likewise, those who abstract groundwater usually do not know how this affects the groundwater regime in their area and that this may contribute to undesirable side-effects such as declining groundwater levels, reduced spring flows and baseflows, degeneration of ecosystems and in extreme cases the loss of an exploitable groundwater resource.

Even if people become aware of the potential impacts of their behaviour on groundwater quantity and quality – either by awareness campaigns or by experiencing the negative impacts – this does not mean that they will automatically adjust their behaviour for achieving maximum societal benefit. Human behaviour is driven more by personal motives than by benefits for society at large. The problem is exacerbated by the conflict between the ‘common pool’ characteristics of groundwater and the fact that people in many parts of the world still consider groundwater ownership or user rights on an individual basis and directly linked to ownership of land. This perception is an enormous obstacle to exploiting groundwater systems optimally as a ‘common property resource’. Gradually, governments of many countries have recognised this problem and as a result there is a trend in redefining legal groundwater ownership as national property, with regulatory and control powers being held by the government. Nevertheless, many obstacles remain, such as dealing with existing private groundwater ownership rights and the lack of agreed principles for groundwater tenure.

4.4 Other factors

Several other factors contribute to the need for improved groundwater governance. Primarily, land use is steadily becoming more intensive in many parts of the world, which is often commensurate with significant impacts on groundwater recharge and increased pollution risk. This does not only refer to agriculture, but also to urbanisation and industrial development. Likewise, as mentioned before, the use of the subsurface is quickly expanding for a wide range of purposes: not only for mining and withdrawal of oil and gas, but also for geothermal energy development, waste disposal, temporary storage (e.g. carbon dioxide capture and storage) and construction into the underground space (subways, parking space, etc.). Figure 4.5 gives an impression of the depth ranges typical for these subsurface uses. Ignoring the interdependence between groundwater and all these activities at or below ground surface may produce unpleasant surprises. Boreholes into the earth’s crust have reached great depths, but technical and economic constraints are a limitation to pumping heads, in particular for groundwater withdrawal (see Box 3).

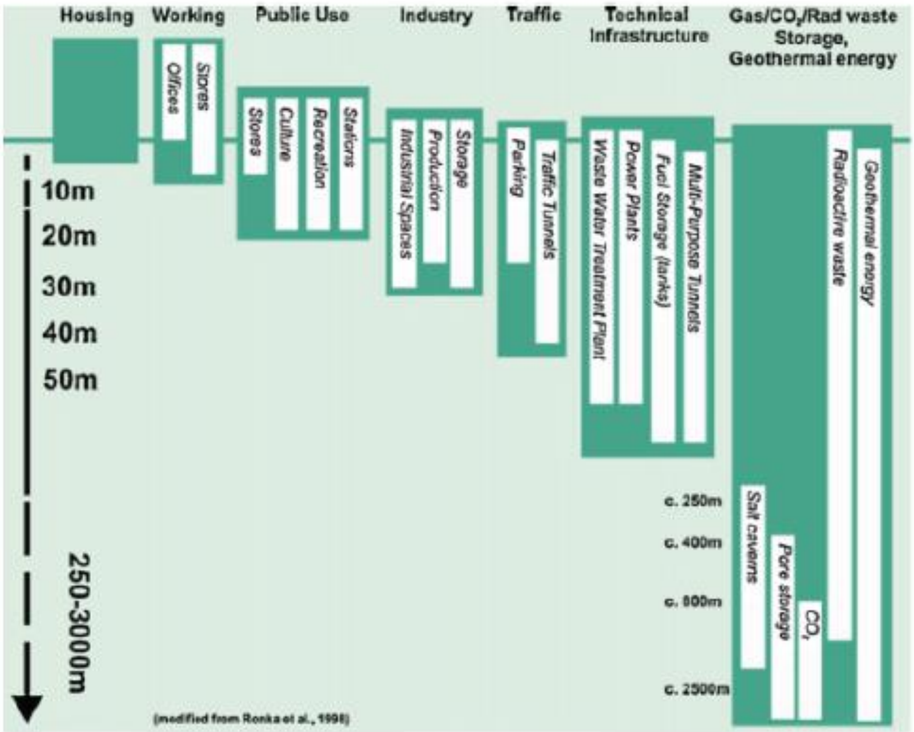


Figure 4.5 Feasible depth ranges for subsurface uses other than groundwater abstraction (Van der Gun et al., Thematic Paper 10; based upon Ronka et al., 1998).

Climate change has the potential to amplify all of the above factors. Despite many uncertainties, it is clear that climate change will exert considerable influence on the water resources conditions of most areas in the world. The challenge is to simultaneously protect vulnerable groundwater systems and use the buffer capacity of groundwater to mitigate increasing water scarcity problems.

Box 2: The limits to drilling into the Earth's crust

Groundwater, oil and gas are most efficiently abstracted by wells and the first hand-dug wells are dated to 10 000 BC. The deepest hand dug well (385 m) for water supply purposes was completed in 1858 at Woodingdean in southern England. The first drilled wells were constructed using percussion techniques to extract natural brines for salt production in Sichuan, China around 2 000 years ago. Between the 3rd and the early 19th century (1835), the depth drilled increased from 140 m to over 1000 m. Since then the capacity to mechanically drill deeper boreholes has steadily increased and the current depth record is held by the Kola super-deep, scientific investigation borehole in Russia at 12 262 m. The deepest water wells rarely exceed 1 500 m and currently the deepest oil wells rarely exceed 7 500 m vertically.
Oil and gas wells are the second most wide-scale intrusion into the underground space after water wells.
Since 1950, 2.6 million oil and natural gas exploration and production wells have been drilled in the United States of America (USA): in 2009 there were 363 107 producing oil and 460 261 producing gas wells[2] in number. According to the American Ground Water Trust, the number of domestic water wells in the USA exceeds 15 million and there are over 250 000 public water supply wells: during 2012 some 600 new water wells are drilled each week in the USA.
Extracting groundwater from wells becomes increasingly technically and economically restricted as the pumping head increases. Positive-displacement reciprocating pumps can be used to lift groundwater from considerably more than 1 500 m, yield performance and efficiency limits their economic application for large-scale groundwater abstraction. The head limit for regular commercial 200 mm electric submersible water pumps is 600 to 650 m but high performance 750 kW multistage submersible pumps used in oil wells can handle heads up to 3 700 m.

Van der Gun *et al*, Thematic Paper 10

4.5 The main challenges related to the physical environment

Given the general objective to keep groundwater systems in such a state that they can perform their many functions in a sustainable way, the primary challenges are to *control groundwater levels* and to *prevent groundwater quality degradation*. Other relevant functions of groundwater, as mentioned, include the role of groundwater in maintaining a stable land surface (i.e. preventing land subsidence), the supply of baseflow to streams and maintaining the health of wet ecosystems.

Controlling groundwater levels in stressed aquifer systems may include measures to augment the resource and measures to reduce the demands for groundwater (demand management; conjunctive use). It should be ensured that the allocation of costs and benefits of these measures is consistent with government policies and societal preferences. Most of the measures devised for controlling groundwater levels and quality intend, in one way or another, to change or regulate human behaviour. This underscores the importance of significant stakeholder involvement in groundwater management and governance.

But groundwater resources management and governance are not only a response to threats and problems. They may contribute also to *achieving a greater benefit from groundwater*. In some cases, this is possible by abstracting and using more groundwater or by expanding groundwater use to unorthodox purposes (e.g. producing geothermal energy). In many other cases there is scope for increasing the benefits from groundwater by reallocation to higher-valued social or economic uses.

[2] See United States Energy Information Agency website (http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html).

5. Elements of a groundwater governance framework

5.1 Groundwater resources management measures

Control of groundwater quantity: water levels and stored volume

Groundwater quantity control measures have the purpose of avoiding or eliminating groundwater overexploitation. These measures fall into three broad categories: (a) augmenting the groundwater resource and protecting recharge areas ('managed aquifer recharge' or MAR); (b) using alternative supplies; and (c) demand management. Figure 5.1 shows schematically how a combination of these measures may turn an overexploited aquifer into an aquifer in dynamic hydrological equilibrium, where groundwater withdrawal does not cause unacceptable negative impacts.

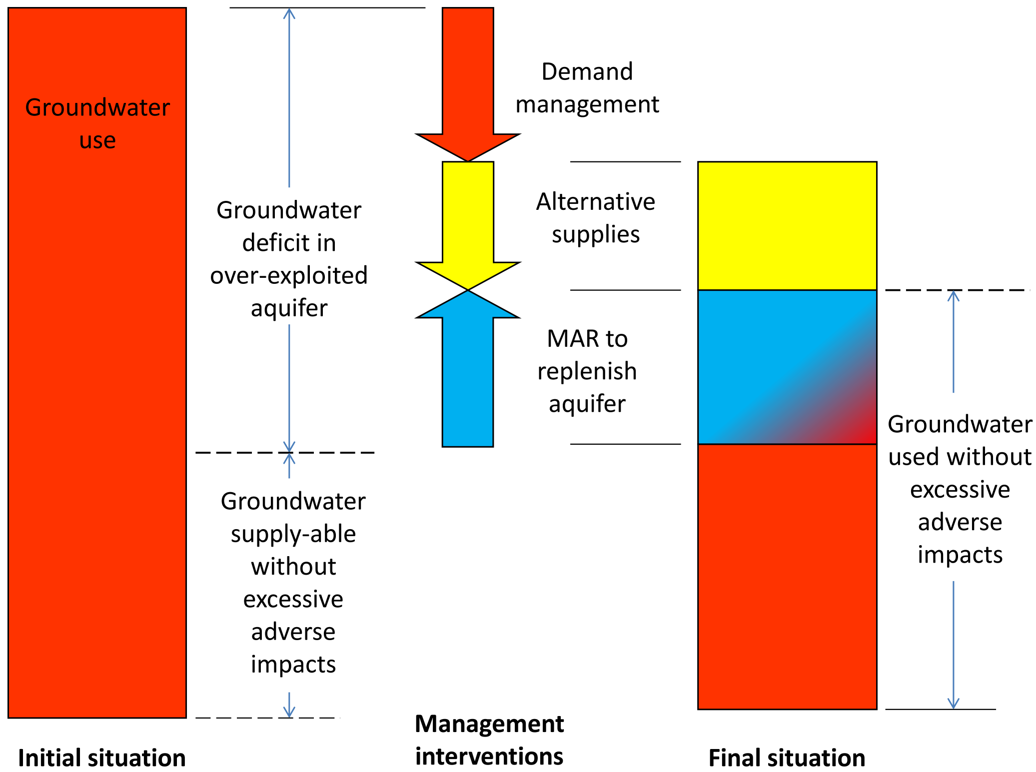


Figure 5.1 Management interventions to convert an overexploited aquifer into an aquifer from which groundwater is withdrawn without causing excessive adverse impacts (Dillon et al., Thematic Paper 4).

Managed aquifer recharge (MAR) is a technical activity by which additional water from an external source (streams, lakes, urban stormwater, treated sewage effluent, desalinated seawater) is recharged into an aquifer in order to augment its renewable volume. MAR makes use of a variety of methods and infrastructural works (recharge dams, sand dams, subsurface dams, recharge wells, recharge basins, barriers, bunds, etc.) and the schemes vary from very small to large (see also Figure 5.2). MAR augments and sustains groundwater storage. Consequently, it increases the quantity of groundwater to be abstracted per unit of time without causing unacceptable negative side-effects.

Tapping alternative supplies to satisfy part of the water demand, e.g. from surface water sources, is a method to reduce the abstraction from an intensively exploited aquifer. Together with MAR, sourcing alternative supplies belongs to the category of 'conjunctive management and use of groundwater and surface water'. The opposite of tapping non-groundwater supplies – tapping groundwater to supplement temporarily scarce surface water (making use of groundwater's buffer capacity) – is part of the same category. Conjunctive management and use approaches refrain from looking at groundwater and surface water systems in isolation from each other, but pay due attention to their physical interconnection and the interdependency of the demands for, and use of, water resources.

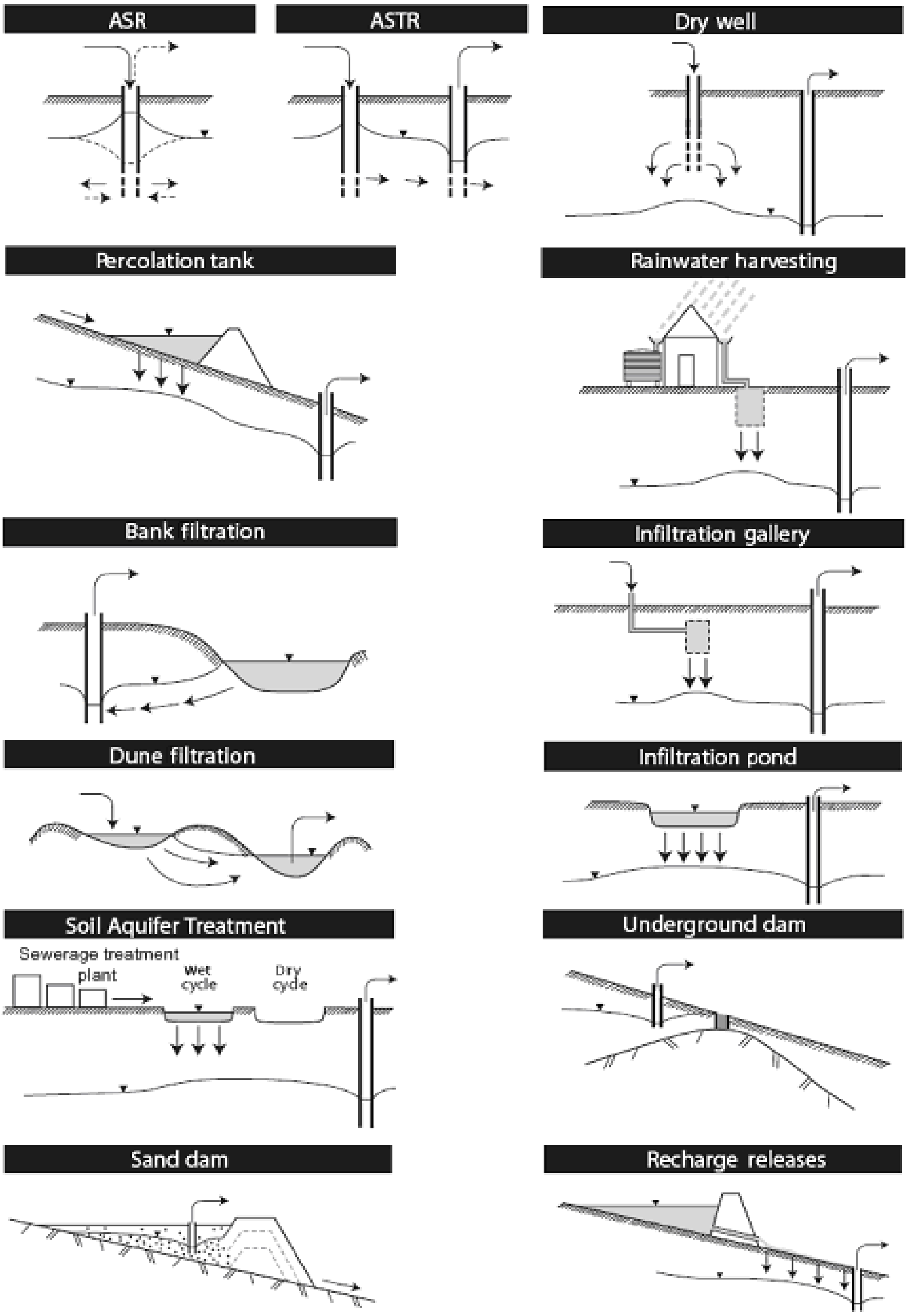


Figure 5.2 Types of managed aquifer recharge (Dillon et al., Thematic Paper 4; adapted from Dillon, 2005).

Measures of the third category – demand management – are non-technical and rely on influencing human behaviour. To this end, regulations may be enforced *(rights and regulations approach)*, incentives and disincentives may be used *(incentives-based approach)*, and/or responsibility for groundwater management may even be delegated to the local level *(subsidiarity approach)*. Common types of regulations in this context are related to permits for drilling wells and for abstracting groundwater. If permit systems have been introduced by mandated groundwater management institutions, then applying for a permit is obligatory (usually above a certain threshold) and ignoring the corresponding formal decision is in contravention of the law. Demand management by creating incentives or disincentives, is an indirect measure and less compelling in general. The incentives or disincentives are commonly produced by economic instruments, such as abstraction fees, energy prices (including subsidies and taxes), subsidies for adopting desired practices (e.g. higher water use efficiencies) and credits for new wells and pumps. But also non-economic tools are used in some cases, e.g. awareness campaigns and limiting energy supply.

It should be ensured that the allocation of costs and benefits of the implemented measures is consistent with government policies and societal preferences. This holds also for any of the measures mentioned below. The strong reliance of the measures on human behaviour underlines the importance of stakeholder involvement in groundwater resources management.

Protecting groundwater quality

Protecting groundwater against pollution and preventing poor-quality water from migrating into or through valuable aquifer systems are two important components of groundwater quality control.

Pollution control measures focus primarily on eliminating or controlling sources of pollution (see Table 5.1). This includes technical measures such as constructing adequate sewerage systems, treating sewage and other wastewaters, ensuring that landfills (waste dumps) are properly designed and removing buried oil tanks that may produce leakage risks. Other measures attempt to influence human behaviour. Again, the main instruments used are legally binding regulations and incentives/disincentives. For example, some regulations may prescribe obligatory provisions for treatment or storage of potentially polluting substances, others may impose restrictions on land use practices in certain groundwater protection areas (e.g. related to the use of fertilizers and pesticides) or prohibit the use of certain substances anywhere. Incentives and disincentives that attempt to reduce pollution include awareness campaigns and pollution fees (*'polluter-pays-principle'*), respectively.

A classical example of undesired migration of poor-quality water is seawater intrusion into coastal aquifers as a result of groundwater withdrawal (see also Figure 4.3). An appropriate measure to prevent seawater intrusion is to reduce groundwater abstractions close to the sea in coastal aquifers; well drilling permit systems are convenient instruments for this purpose. Arresting migration is important in cases where part of the groundwater system is already polluted. Physical confinement is feasible only in exceptional cases, but hydrodynamic isolation techniques (creating 'zero gradient around the polluted zone') are more widely applicable. Remediation of polluted groundwater by 'pump-and-treat' is practiced in cases of localized point pollution.

Pursuing highest benefit from groundwater to society

Groundwater resources management and governance are not only a response to threats and problems, but they may also contribute to *achieving greater benefits from groundwater use*. In some cases this is possible by abstracting and using more groundwater or by expanding groundwater use to unorthodox purposes. In many other cases, there is scope for increasing benefits from groundwater by reallocation to socially or economically more profitable uses. Governments may have strategies to improve urban or rural water supplies, or ambitions to enhance overall economic or social welfare. Well drilling programmes have been widely used to pursue such goals, such as the Millennium Development Goal related to improved drinking water supply. Conflicts of interest (e.g. urban versus rural water supply) can be addressed by the aforementioned regulatory instruments in combination with clearly defined and accepted priorities. Higher socio-economic benefits ('more jobs and income per drop') can be achieved by creating incentives (awareness, technical assistance, subsidies, etc.) for individuals who adopt approaches that are likely to increase the economic efficiency of water use. But also the *in-situ* benefits from groundwater (related to its environmental functions) should be valued and protected or, where possible, even enhanced. In addition, innovative uses of groundwater – for example the development of geothermal energy – will require special projects by governments and/or private parties to explore the local conditions and implement exploitation programmes.

Table 5.1 Some methods for controlling pollution sources to be considered for groundwater quality governance (Custodio, Thematic Paper 1)

Pollution source	Possible control method
Landfills	Regulation of sitting, operation and closure Monitoring the site
Underground storage tanks	Periodic inspection Pressure testing Improved construction
Spill, leaks, improper disposal of hazardous wastes	Control of distribution and use Storage regulations Effective fining of malpractices Mandatory inspection of: ● transportation ● storage ● use Fast removal of spill damage Monitoring the facility
Agrochemicals: ● fertilizers ● pesticides ● herbicides	Introducing good agricultural practices: ● application limits ● timing of application ● application methods ● permits for use Ban dangerous substances Control the disposal of used containers
Feedstock wastes	For intensive farms: ● sufficient storage facilities ● document waste use and disposal ● control of pharmaceuticals use For extensive farms: ● Limits to animal spatial density
Septic systems	Regulation of ● sitting ● installations Periodic inspection Licensing installers

5.2 Creating the enabling environment for groundwater resources management

Area-specific information and diagnostics: making groundwater visible

Groundwater resources management should be guided by area-specific information that enables: (i) the characterisation of the groundwater system of the management unit under consideration – aquifer system or river basin; and (ii) understanding of trends and impacts of groundwater management measures, on the basis of observed time-dependent variables. This information should cover all relevant aspects related to groundwater and its use and should be collected with the degree of detail and accuracy that is required for deriving reliable diagnostics on the *status quo* related to groundwater, plus the trends and issues to be addressed. Multidisciplinary assessment studies and systematic monitoring programmes of time-dependent variables are needed to generate the area-specific information. These tend to be expensive and time-consuming, meaning that they should be planned as a structural component of groundwater governance, thus not be postponed until major problems will have appeared.

Legislative and regulatory framework

The legal framework for groundwater management forms the basis for regulating access to groundwater resources and the right to abstract. Legal frameworks are also instrumental in setting criteria for groundwater

allocation, dealing with protection against depletion and pollution, establishing monitoring and planning tools and arranging for stakeholder participation. In relation to transboundary aquifers, special legal and regulatory frameworks may focus on transboundary impacts, harmonization of activities and cross-border cooperation.
At the country level, groundwater ownership and user rights are fundamental issues to be defined by the law. There is a worldwide trend to vest water ownership or control in the state and to separate it from land ownership. This defines water as a 'public good'; however people often continue to perceive groundwater as a 'private good'. Customary, community-based and informal arrangements still govern access to groundwater in large parts of the world. If new formal rights are defined, then they should be harmonised with customary rights. An important issue to be addressed by the law is liability in the case of external impacts of human activities; the 'polluter pays' principle is a case in point. Groundwater-related regulations, based on the principles stipulated in the law, are needed to ensure transparent and consistent law enforcement and also the institutional mandates for enforcement need to be based on the law.

The legislative and regulatory framework for groundwater contains a number of important instruments at the regional and international level. Regional instruments include the UNECE Convention on the Protection and Use of Transboundary Water Courses and International Lakes (Helsinki Rules, 1992) agreed upon by the member countries of the Economic Commission for Europe and recently opened for global adoption, the Water Framework Directive (2000) as a legally binding instrument for the members of the European Union and its daughter Directive on Groundwater (proposed in 2003) – see also Box 4. The most important global instrument is the Draft Articles on the Law on Transboundary Aquifers, adopted in 2008 by the International Law Commission (UNILC). Similar to the UN Convention on the Non-Navigational Uses of International Watercourses (1997), the Draft Articles are currently non-binding; however the aim is to achieve broad country endorsement. The Draft Articles are a convenient reference for treaties and other legal instruments involving aquifers. Only a few aquifer-specific agreements exist between countries sharing an aquifer: the Genovese aquifer, the Nubian Aquifer System, the North Western Sahara Aquifer System, the Iullemeden Aquifer System and the Guaraní Aquifer System. Groundwater is also included as a component in a number of bi- or multilateral treaties on rivers or lakes.

Box 4: EU Directives

EU directives are supranational law which is unique in nature. Supranational law is neither international law, which is binding only between and among states, nor domestic law. EU directives are developed in legislative processes at the EU level but then have to be transposed into domestic law, i.e. the content of EU directives becomes part of the domestic legal system. In case members states fail to transpose EU directives the European Commission can initiate an infringement procedure before the European Court of Justice which may impose financial penalties. Under certain circumstances, EU directives may also be directly effective in member states' national legal orders.

Mechlem, Thematic Paper 6

Groundwater legislation and regulation should take into account the linkages between groundwater, surface water and all types of subsurface and land uses. Laws and regulations should also be drafted with due consideration of macro-level policies, institutional capacities and other relevant local factors. They may also define the roles and responsibilities of groundwater user groups and other non-governmental entities in relation to those of public institutions.

Institutions

Institutions, defined here as the formal organizations or informal groups created to pursue specific goals, are the leading actors in groundwater governance and management. All aspects of groundwater governance and management should be covered by an institution in one form or another. Consequently, most governments have established, among others:

- institutions for assessing and monitoring groundwater, as well as for identifying and studying relevant issues;
- institutions for developing groundwater management strategies – often incorporated in IWRM strategies – and area- or aquifer-specific strategic planning;

- institutions responsible for operational management, which includes the implementation of technical measures, the enforcement of laws and regulations, the provision of incentives or disincentives and the interaction with local stakeholders and the general public.

Apart from government organizations there are other institutions that play a role. They include scientific institutes and consultancy firms providing services to the government, but also water supply companies, mining companies, industries, agricultural organizations, water user associations (see Box 5), environmental action groups and others. Some of the local institutions have a long legacy, e.g. those around shared springs or devoted to qanat systems. All these groups have their own agenda and priorities, and as a result there are often conflicting interests. It is a challenge to establish open communication, mutual trust and effective cooperation in order to develop balanced courses of action that do justice to the interests of all groups.

Box 5: Groundwater User Associations in Spain, the US and Mexico (COTAS)

The legislation of a number of countries provides for the establishment of (ground-)water user associations or aquifer management organizations, for instance in Spain (Lopez-Gunn and Cortina 2006), Mexico, Australia and the western states of the US. They have been established especially where aquifers are at risk of being degraded or depleted. For instance, the Spanish Water Law of 1985 makes the establishment of groundwater user organizations compulsory in overexploited aquifers (Hodgson 2006, p. 41). In a number of western states of the US groundwater management or conservation districts, a form of water users association, have been established in respect of about 89 percent of groundwater resources. They are controlled by local users and may set limits on pumping and wells, adopt groundwater management and development policies and programmes, and propose water allocations criteria. In Mexico, where groundwater resources are severely overexploited, COTAS (Comités técnicos de aguas subterráneas – technical groundwater committees) have been created. They are civil society organizations, whose set up has been carefully facilitated by the National Water Commission and who are supported financially by the public hand. Inter alia, the COTAS support the implementation of groundwater management plans, support the government in groundwater rights administration, provide services to groundwater user, support consensus-building for future integrated water resources management and establish dialogue with and improving data on groundwater users (e.g. by helping the water administration to validate, update and correct databases on wells)

Foster, Garduño and Kemper (2004).

Awareness raising, communication and stakeholder participation
The general public does not know very much about groundwater. Therefore, to obtain public support for groundwater plans and interventions there is a need to make the general public aware of relevant local groundwater features and inform them on planned action. This is even more crucial if people are expected to change their behaviour or to play an active role as stakeholders in the management process. Transparency, accountability and good communication on decisions and planned action builds trust, which is essential for developing smooth co-operation.

Effective public participation can be achieved through different modalities and degrees of involvement. The approaches range from informing or consulting stakeholders to full delegation of groundwater management responsibilities. Local conditions and expectations about feasibility and effectiveness determine which method is chosen. Experience and research have found that stakeholder participation can be improved by: building on existing social capital, promoting equity and inclusion, starting in areas of good potential, adopting a step-by-step process and adapting to lessons learnt.

Policies, strategy development and operational activities
Groundwater governance distinguishes decisions and actions at three levels: the policy level, the strategic level and the local or operational governance level.

Activities at the *policy level* have a strong political dimension and result in setting overall objectives and priorities. These have to be adapted to the local context and be tailored to the size and nature of reliably identified critical issues and opportunities. Which generic types of management units to be chosen, e.g. aquifers versus river basins, or aquifers versus groundwater bodies, are also defined at the policy level. Opting for a IWRM approach to address groundwater is also a decision at policy level.

Governance at the *strategic level* establishes institutions and defines strategies and instruments in order to achieve the policy goals set. At this level it is decided whether, to what extent and how to incorporate groundwater resources management in IWRM and to harmonise it across sectors. This requires sufficient information and knowledge, thus governments should be persuaded to invest in these components and the institutions in charge. Next, the main paradigms to be adopted are identified and defined, e.g. sustainable development, market approaches, adaptive management and decentralisation. These paradigms should be consistent with those adopted in a wider context, for water, the environment and natural resources in general. With reference to influencing the behaviour of individual stakeholders, three approaches are commonly distinguished: a rights-and-regulation approach, an incentives-based approach and a subsidiarity approach. Rights-and-regulatory approaches are very demanding to implement and meet usually resistance by stakeholders. However, for large and formal sector users they often tend to be most feasible and the best option. Adjusting the incentives structure is a mechanism that even a weak government can undertake, but the political feasibility of adjustments is often a problem and they can have unexpected adverse effects or unintended side-effects. Delegating governance to the local level can produce good results and requires a framework for encouraging subsidiarity. A mix of approaches will normally be indicated, which requires flexibility, adaptation, and keeping an eye on equity. Finally, in anticipation of conflicts over groundwater becoming more frequent, it is worthwhile to develop conflict resolution mechanisms.

It is at the *local or operational level* that measures are implemented. Within the boundaries defined by policy and strategy, an operational plan can be made to guide the systematic implementation of measures and other interventions, at the same time to be used for communication with stakeholders. Partnerships between local stakeholders and public agencies are often an effective approach, but these require long-term commitment on both sides. However, there is a risk that participation may reflect and even reinforce existing inequalities. Empirical evidence suggests that local collective management can be effective in certain settings.

5.3 Constraints and opportunities

Constraints related to knowledge, perceptions, experience and vision

Insufficient information on local conditions forms often a fundamental constraint to groundwater governance. This information deficit may refer not only to the physical groundwater systems, but also to water demands and use, socio-economic factors, as well as to the physical, socio-economic and political characteristics of interconnected policy areas. If this is the case, investments in studies and/or monitoring evidently have to be made to provide a reliable basis for diagnostics and the development of area-specific strategies and plans.

What decision-makers, planners and local stakeholders know about the local groundwater-related conditions usually lags behind the available information. Very often a limited knowledge of both general groundwater principles and the local situation causes decision-makers to have a poor perception of the groundwater realities in their area and the opportunities and problems offered. This weakens the motivation to play a constructive role in groundwater governance. Public awareness campaigns can help eliminate this constraint.

Furthermore, those who are professionally involved in strategy development and planning for groundwater governance, depend on their own experience and knowledge, inevitably with inherent limitations. For example, the potential role of groundwater in public water supply is often underestimated or even ignored (which is a lost opportunity for more integrated management) and tools for urban water management usually fail to take the time scales of groundwater into account. Further, looking for alternative water sources is often a primary response to water scarcity, rather than analysing the potential offered by integrated water resources management. Methods with demonstrated effectiveness for combating chronic groundwater depletion are not yet widely used, probably because the water resources managers are insufficiently familiar with MAR, conjunctive use and other options, or their organizations lack implementation capacity. Finally, the potential role of the groundwater buffer is often ignored and experience on how to exploit fossil groundwater resources most profitably is still missing.

Other constraints to making a quick start and gaining support

Groundwater is invisible to the general public and it is difficult to untangle its contribution to national welfare from that of surface water. This produces a very skewed public perception of the value of groundwater, and for that reason groundwater does not easily reach the political arena (unless serious problems develop). Additionally, politicians are unlikely to call attention to groundwater governance due to the significant budgets required and the very long reaction times of groundwater systems, meaning it takes many years before the effect of any intervention can be observed. Groundwater management and governance are, unfortunately, politically unrewarding and fraught with political risk.

Constraints presented by specific properties of the groundwater resource

Due to the more or less continuous existence of groundwater over large areas and down to considerable depth below ground surface, groundwater resources assessment is complex and expensive. This is exacerbated by the fact that locally observed state variables often have relatively limited spatial representativeness (this applies in particular to water quality). Abstraction and use of groundwater is highly decentralised and scattered over large areas which makes monitoring and management difficult and expensive.

The inertia of groundwater systems is another significant constraint. Large time lags between cause and effect add difficulty to defining adequate measures and make many undesired changes of state (water levels, water quality) almost irreversible in practice. Errors or lack of required action thus do not remain unpunished. Groundwater depletion and contamination will result in spiralling costs for access to water, claiming valuable economic resources with the poor often suffering the most.

Constraints presented by the overall physical environment

A myopic focus on groundwater systems and groundwater users is unlikely to lead to good groundwater management. In the first place, there are often preferences of the society to maintain certain environmental conditions (protection of ecosystems, springs, baseflows, stability of land surface, etc.), which in practice turn these preferences into constraints to groundwater withdrawal.

Secondly, in parallel to groundwater abstraction and groundwater level control, many other activities are independently carried out in the area, with potential impacts on groundwater quantity and quality. These activities include waste and wastewater disposal, urban development, agricultural land use (including all chemicals used), industrial activities, mining, oil and gas exploration and exploitation, geothermal energy development, subsurface storage, construction and use of tunnels, subways, pipelines, etc. Groundwater governance should require that communications and negotiation with all parties involved be established, allowing in a pragmatic way for a certain level of interferences to be accepted.

Countless well owners have appropriated groundwater and it should be taken into account that they tend to respond more to powerful economic incentives than to the rules that management would impose.

Constraints related to human behaviour and conflicts of interest

Perceived or formal groundwater entitlements based on land-ownership fail to recognise the ‘public good’ nature of groundwater and its environmental role. Human behaviour related to groundwater, therefore, more often aims to achieve personal gain (‘selfish behaviour’) rather than contribute to maximum societal benefit. It is difficult to change human behaviour because groundwater users drawing as competitors from a common pool need external support to guarantee that all comply equally with the same imposed restrictions on groundwater abstraction. This is not only true for groundwater withdrawal, but holds also for abandoning behaviour that easily contributes to groundwater pollution or other forms of groundwater quality degradation. A certain natural resistance to change, delayed recognition of the impacts of abstraction and other human behaviour, and reluctance to address these impacts also play a role. Cooperation and voluntary agreements for changing behaviour may not only be a possibility but rather a logical need. However, evident incentives should enable these. Creating an atmosphere of trust and willingness to cooperate requires serious efforts and sufficient time. Conflicts of interest between individuals or groups that have a stake in groundwater cannot be ignored and require special provisions to find solutions that are acceptable to all (conflict resolution mechanisms, priority setting methodologies, etc.). The urban-rural interface in particular, is a breeding ground for conflicts on groundwater quantity, quality and access. Elsewhere, however, there may be conflicts of interest between those who want to exploit groundwater and activists who want to conserve it for environmental reasons.

Constraints related to institutions and legal frameworks

In many cases, public agencies in charge of addressing water scarcity and mitigating its impacts have limited or even insufficient mandate, capacity and budgets, especially in developing countries. Institutional fragmentation is also very common: separate institutions and governance arrangements do often exist for managing groundwater and surface water – which forms an obstacle to integrated management. Poor communication and co-ordination with agencies active in related fields (water supply, irrigation, mining, oil and gas development, geothermal energy production, etc.) form additional constraints to more holistic approaches in groundwater management.

Community engagement is helpful, but the groups involved may lack community structure, well-defined rights and adequate political representation.

Centralised water supply systems often are unsatisfactory, but attempts to decentralise them have often failed too (e.g. by keeping finances at the central level or by lack of capacity building).

Legislation and regulatory frameworks related to groundwater is insufficient and/or fragmented in many countries. At the global level, the Draft Articles on the Law of Transboundary Aquifers (2008) have been adopted by the United Nations International Law Commission. They represent non-binding 'soft law', providing guiding principles at global level.

Opportunities

Indirect management action for governance seems promising in many settings, but there is currently insufficient experience available to underpin this.

Investment in active awareness campaigns for decision-makers and the general public has the potential to put groundwater and its governance higher on political agendas. Groundwater is certainly more important than most decision-makers probably think and there is much at stake. The advocates of governance and change need to choose their cause carefully, identifying the really critical issues, and preparing and presenting the options persuasively.

Groundwater with its unique buffer capacity will undoubtedly play an important role in mitigating problems caused by climate change and affecting surface water sources and 'green water' much more.

6. Present state of groundwater governance and prospects

6.1 Preamble

The picture presented in this chapter is only tentative, because it is based mainly on expert judgement by the authors of the Thematic Papers and not on a systematic world-wide assessment. Such a comprehensive assessment would require huge efforts and the definition of adequate assessment criteria and indicators. A proposed list of such criteria is shown in Table 6.1. The organization of this chapter does not follow this list systematically, but - for pragmatic reasons – has been adapted to the themes addressed and the information provided in the Thematic Papers.

Table 6.1 Checklist of 21 key benchmarking criteria for the evaluation of groundwater governance provision and capacity (Howard, Thematic Paper 3; modified after Foster et al., 2010)

<table>
<tr><th rowspan="2">TYPE OF PROVISION/ CAPACITY</th><th colspan="3">CHECK LIST</th></tr>
<tr><th>No.</th><th>CRITERION</th><th>CONTEXT</th></tr>
<tr><td rowspan="7">Technical</td><td>1</td><td>Existence of Basic Hydrogeological Maps</td><td rowspan="3">For identification of groundwater resources with classification of typology</td></tr>
<tr><td>2</td><td>Groundwater System Conceptual Model Development</td></tr>
<tr><td>3</td><td>Groundwater Body/Aquifer Delineation</td></tr>
<tr><td>4</td><td>Groundwater Potentiometric Head Monitoring Network</td><td>To establish resource status</td></tr>
<tr><td>5</td><td>Groundwater Pollution Hazard Assessment</td><td>For identifying quality degradation risks</td></tr>
<tr><td>6</td><td>Availability of Aquifer Numerical 'Management Models'</td><td>At least preliminary for strategic critical aquifers</td></tr>
<tr><td>7</td><td>Groundwater Quality Monitoring Network</td><td>To detect groundwater pollution</td></tr>
<tr><td rowspan="9">Legal & Institutional</td><td>8</td><td>Water-well Drilling Permits & Groundwater Use Rights</td><td>For large users, with need of small users noted</td></tr>
<tr><td>9</td><td>Instrument to Reduce Groundwater Abstraction</td><td rowspan="2">Water-well closure or constraint in critical areas e.g. overexploited or polluted areas</td></tr>
<tr><td>10</td><td>Instrument to Prevent Water-well Operation</td></tr>
<tr><td>11</td><td>Sanction for illegal Water-well Operation</td><td>Penalizing excessive pumping above permit</td></tr>
<tr><td>12</td><td>Groundwater Abstraction and Use Charging</td><td>“Resource tariff” on larger users</td></tr>
<tr><td>13</td><td>Land-Use Control on Potentially-Polluting Activities</td><td>Prohibition or restriction since a potential groundwater hazard</td></tr>
<tr><td>14</td><td>Levies on Generation/Discharge of Potential Pollutants</td><td>Providing incentive for pollution prevention</td></tr>
<tr><td>15</td><td>Government Agency as 'Groundwater Resource Guardian'</td><td>Empowered to act on cross-sectoral basis</td></tr>
<tr><td>16</td><td>Community Aquifer Management Organizations</td><td>Mobilizing and formalizing community participation</td></tr>
<tr><td rowspan="3">Cross-Sector Policy Coordination</td><td>17</td><td>Coordination with Agricultural Development</td><td>Ensuring 'real water saving' and pollution control</td></tr>
<tr><td>18</td><td>Groundwater-Based Urban/Industrial Planning</td><td>To conserve and protect groundwater resources</td></tr>
<tr><td>19</td><td>Compensation for Groundwater Protection</td><td>Related to constraints on land-use activities</td></tr>
<tr><td rowspan="2">Operational</td><td>20</td><td>Public Participation in Groundwater Management</td><td rowspan="2">Effective in control of exploitation and pollution with measures and instruments agreed</td></tr>
<tr><td>21</td><td>Existence of Groundwater Management Action Plan</td></tr>
</table>

6.2 Available information

Fundamental to groundwater governance is a correct and sufficiently detailed understanding of the local groundwater resource, its use and the overall setting. This requires much more than hydrogeological information, but also information on hydrology, total water demands and use, socio-economic conditions, ecosystems, the environment, agricultural practices, etc. It is impossible to present here a full, balanced picture of the current availability of such information in different parts of the world. Instead, only a few remarks will be made:

- The availability of local information relevant and needed for groundwater governance varies enormously from country to country and also between areas inside countries.
- In many countries, very significant progress has been made during the last few decades regarding the availability of such information and in particular the access to this information (Internet). Nevertheless, information on the groundwater conditions is in numerous areas around the world still minimal or missing.
- International cooperation programmes have contributed very significantly to the improvement of groundwater related information in many developing countries.
- At the global level, several initiatives have been taken by international organizations for projects and institutions that intend to enhance and disseminate world-wide area specific information and knowledge (WHYMAP, ISARM, IGRAC, TWAP, etc.).
- The private sector – in particular the mining industry – possesses very substantial information on the subsurface, but most of this information is not yet available to third parties.
- Monitoring networks and other methods to systematically observe time-dependent groundwater variables are the weakest part of the information chain. Monitoring networks are often quickly abandoned in times of scarce means and if started as a project activity they usually stop not very long after the project's expiration. In some countries, special institutional or legal arrangements affect the continuity of monitoring activities very positively, e.g. in India (Groundwater Estimation Methodology used as a basis for management decisions) and in the European Union (obligations imposed by groundwater daughter directive of the WFD).

It is expected that, in the near future, planners and investigators will tend to broaden the scope of information to be collected, guided by a shift in focus from hydrogeology and water supply to the more holistic approaches of groundwater resources management and groundwater governance. Without strong advocacy for the need and benefits of additional information, the continuity of assessment and monitoring seems at risk.

6.3 Dealing with main issues of concern

The geographic variation of the main issues in groundwater resources management and governance is even higher than that of the state of information. A few main issues will be briefly reviewed.

Control of groundwater levels

This is in the first place an issue in areas where artificial drainage is needed to make the land suitable for residential purposes and land use (e.g. in flat coastal lowlands such as in The Netherlands), or to facilitate mining and other subsurface activities (scattered around the world). Traditions and practices of artificial drainage have been long established, but they are subject to modifications due to technological innovations.

More complex from the point of view of management and governance is the control of groundwater levels (which also means: control of groundwater volume stored) in areas where groundwater withdrawal is of sufficient intensity to modify the local groundwater conditions and budget markedly. Figure 6.1 distinguishes schematically four typical stages of groundwater development intensity, each with its own impacts of the groundwater budget.

The first stage represents situations where groundwater abstraction is absent or insignificant. The hydrogeological regime is characterised by long-term stability in groundwater levels, groundwater storage and natural groundwater discharge (dynamic equilibrium). If groundwater abstraction becomes significant but still moderate, then groundwater levels will decline (reduction of storage) and the natural discharge will be reduced to some extent, until after some time a new dynamic equilibrium is established (stage 2). Under a more intensive abstraction rate, groundwater levels and natural discharge will further decrease until a new equilibrium is reached where all natural groundwater discharge has stopped (stage 3). At higher groundwater abstraction rates, a dynamic equilibrium can't be established anymore: groundwater levels are declining progressively and groundwater storage is depleted (stage 4).

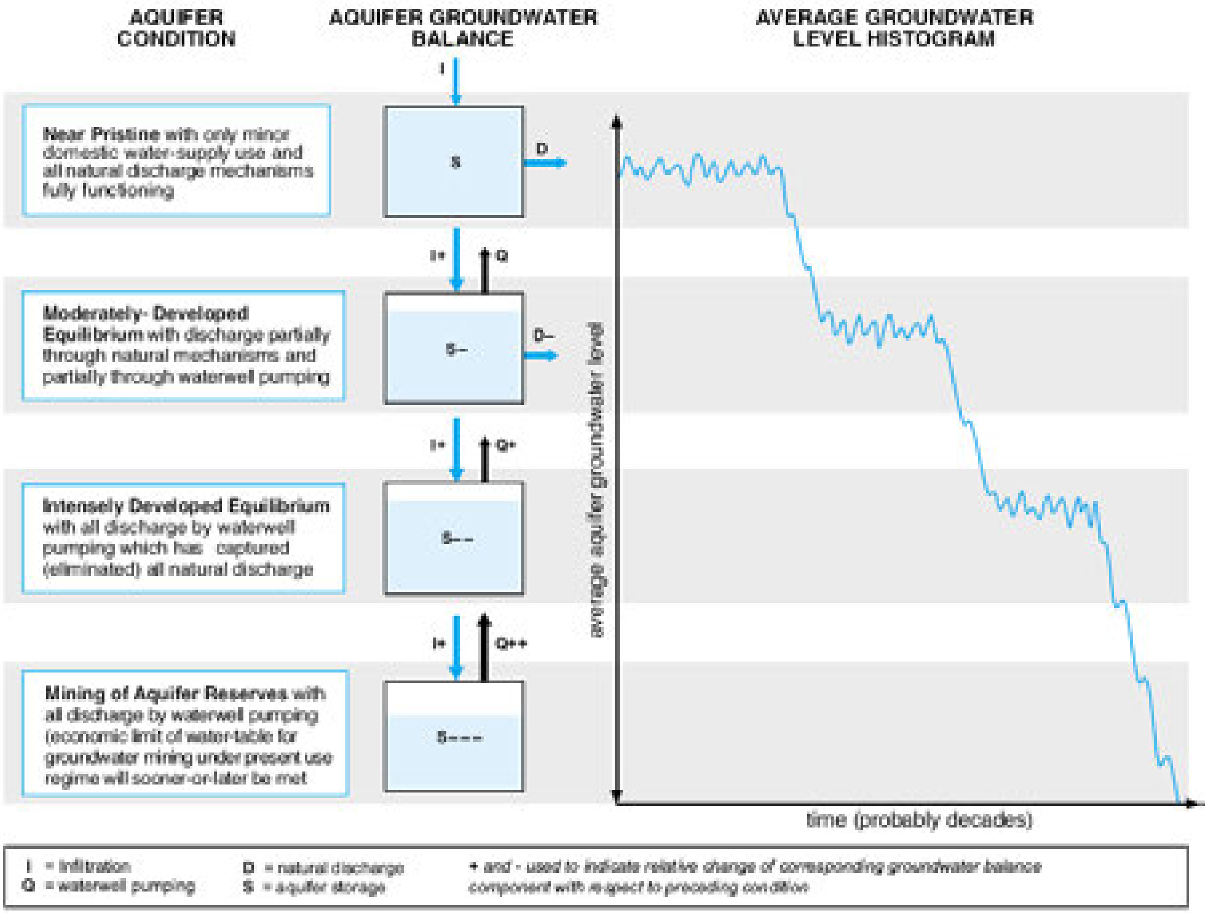


Figure 6.1 Typical stages of groundwater development and the corresponding impact on the natural discharge and storage of groundwater bodies (source: GW-MATE, 2009).

Stage 1 conditions do not require any management interventions. Areas that can be classified as stage 2 are abundant around the world, in particular in humid zones. The groundwater levels under the new equilibrium conditions usually have not declined much compared to the pristine situation, which means that there is not yet a strong need to implement measures of control, unless there is scope for undesired side-effects such as land subsidence or degradation of ecosystems. In practice, where land subsidence in urban areas develops, it usually is addressed by implementing measures, but controlling the degradation of ecosystems mainly gets attention in relatively rich developed countries. Stages 3 and 4 typically occur in almost all moderately- to densely-populated areas in the arid and semi-arid zone. Depletion of groundwater storage develops spontaneously in such areas, given the high profitability of groundwater, especially as a source for irrigation. Once the diagnosis of progressive depletion (stage 4) has been made, a choice has to be made between possible management scenarios for the near future. Figure 6.2 shows the main options.

Gradual recovery from an undesired state of depletion is usually an unfeasible target in arid and semi-arid zones, but there are exceptions like the Great Artesian Basin in Australia and the Alluvial Basins of Arizona. Even achieving a general stabilization (which means returning to stage 3) is, for many aquifers in such zones, an overambitious target given the socio-economic importance of the water pumped, the scarcity or absence of alternative sources of water and the general political and socio-economic context. In case continuous depletion is unavoidable, then 'orderly depletion' should be adhered to with a clear plan for what to do after the groundwater resources have been completely exhausted (exit strategy). No real cases of such 'orderly depletion' are known, neither for renewable nor for non-renewable groundwater resources.

Licensing systems for drilling and/or pumping, with the objective of restricting groundwater withdrawal, have been introduced in many countries. Although satisfactorily operational in some countries, often these systems

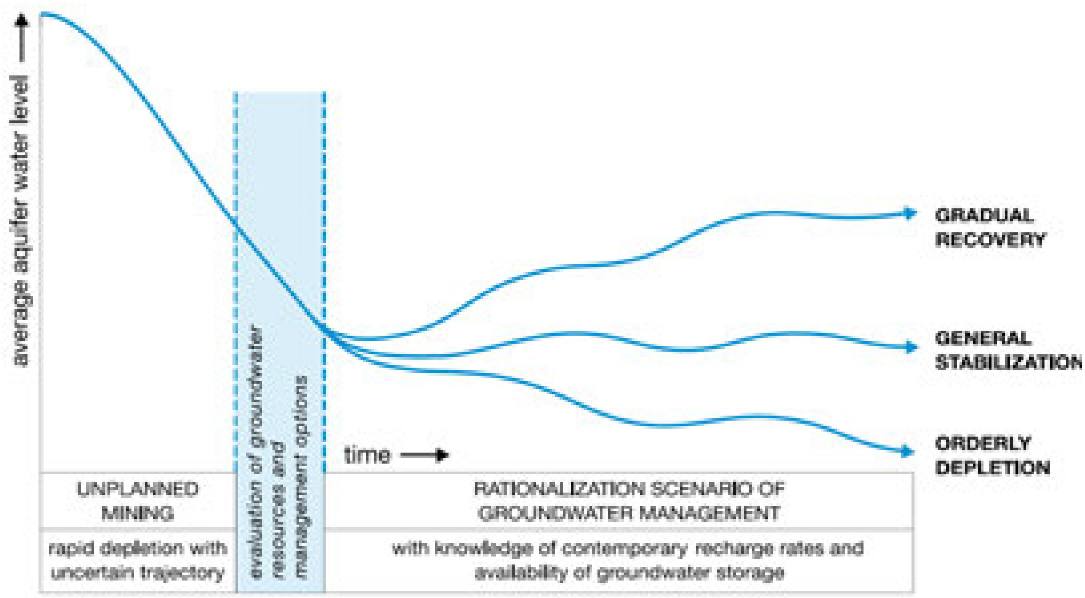


Figure 6.2 Targets for groundwater resources management in 'rationalization scenarios' following indiscriminate and excessive exploitation of groundwater (source: GW-MATE, 2005).

are not effective in practice, because of the absence of strict enforcement, the reluctance of pumpers to comply, the lack of clear criteria for granting or refusing a licence, or the licensing system simply considered as a means to generate income for the government (license fees).Some countries opt for incentives and disincentives to influence pumping behaviour. Most commonly this is by means of energy pricing (subsidies) or limiting access to energy.

Another approach to achieving a desired rationing target or to prevent an excessively stressed groundwater regime from developing is managed aquifer recharge and other forms of conjunctive management of ground-water and surface water resources. It is already being applied in many parts of the arid and semi-arid zone, but there is scope for expanding it considerably in the near future. In contrast to measures that restrict groundwater pumping, these methods are less likely to be opposed by groundwater users.

Groundwater quality control

As mentioned in Chapter 5, groundwater quality control addresses two main types of water quality degradation: pollution by the influx of undesired substances produced by humans; and the flow of poor-quality water into masses of fresh groundwater of good quality. Pollution is the more ubiquitous of the two and poses the largest threat to the groundwater resources. There are many sources of groundwater pollution: sewage, solid waste, fertilisers and pesticides used in agriculture, accidental spills, industrial waste products, improper waste disposal practices, etc. It is important to note that polluters and those who abstract groundwater are different groups: polluters do not necessarily have a stake in the groundwater resources they affect. Groundwater pollution has encroached in nearly all shallow aquifers around the world underlying either densely populated zones or intensively-used agricultural land. The pollution process is virtually irreversible. A wide range of measures has been implemented to halt pollution, but mainly in relatively wealthy, developed countries: sewerage systems and adequate solid water management, land use restrictions in groundwater recharge areas, groundwater protection zones around important well-fields, obligatory treatment of industrial waste waters, prohibition of the use of certain chemicals, pump-and-treat projects, coordination between groundwater management and land-use planning, etc. They certainly have positive effects, but especially diffuse pollution caused by agriculture remains difficult to control. It should be noted that over time there has been substantial progress in improving the detection level of groundwater contaminants (see Table 6.2). This has influenced the groundwater pollution control agendas.

Table 6.2 Progress in detection levels of possible groundwater contaminants (Custodio, Thematic Paper 1; adapted from Ronen et al., 2012)

Moment	Contaminant	Level of detection
1950s	Major solutes Nitrates Dissolved organic carbon	mg/L (10^{-3} g/L)
1960s	Heavy metals Rare heavy metals Pesticides and herbicides Hydrocarbons	µg/L (10^{-6} g/L)
1980s	VOCs (volatile organic carbons) Chlorinated solvents	ng/L (10^{-9} g/L)
1990s	Hormones and endocrine disruptors Antibiotics Other emergent contaminants	pg/L (10^{-12} g/L)

Groundwater quality degradation may also take place as a result of groundwater abstraction, causing intrusion of seawater into coastal aquifers, upconing of connate brackish or saline groundwater overlain by fresh groundwater or other migrations of poor quality groundwater into freshwater bodies. Many aquifers around the world, especially in coastal zones, have suffered from salinization processes by these mechanisms. Measures for quality reversal or for preventing continued salinization – including reducing or reallocating abstractions, artificial recharge and intrusion barriers – have been implemented successfully in several of these aquifers. In general, it is reasonably known where seawater intrusion and other abstraction-induced forms of quality degradation may occur. Implementing measures for control is usually not controversial, because stakeholders easily understand the need for it and see that it will benefit them.

The overall prospect for groundwater quality is that some degradation will continue to occur: increasing salinity, nitrate build-up, deleterious organic compounds and emerging contaminants (PCCPs, EDCs). Future climate change may influence groundwater quality according to how it will modify recharge. However, land use changes may in many parts of the world have greater effect on recharge and on groundwater quality than climate change. Finally, it needs to be highlighted that correcting groundwater quality degradation is much more expensive that preventing it; this should be taken into account when allocating budgets for groundwater quality control.

Allocating groundwater and enhancing its beneficial use

In most parts of the world, groundwater exploitation has largely developed as a private activity, triggered by the needs of individuals or specific groups and without coordination between groundwater exploiters. Only after it has become so intense to cause interference between wells or significant declines of groundwater levels, then in many cases communities have become aware that some kind of regulation would be useful, or, in advanced cases, even conflict resolution mechanisms are required.

Many countries that have been confronted with such conditions have defined relative priorities between water use sectors, usually assigning the highest priority to groundwater use for drinking water and other domestic purposes. Often, however, it is not clear whether such a declared allocation priority is also made effective in practice, by playing a decisive role in granting abstraction permits or any other measures.

The urban and semi-urban environment forms a special case, likely to produce severe urban-rural tensions. Without urban spatial and infrastructure planning, opportunities to provide adequate water and sanitation services are seriously compromised. Left unaddressed, urban slums threaten both national and international security, human health, and environmental sustainability. It seems that current problems with urban groundwater management will only be resolved if governments work in association with groundwater users rather than attempting to regulate and control them.

Conflicts that may arise as a consequence of externalities produced by groundwater exploiters need conflict resolution mechanisms. Apart from the obligation to supply financial compensation in cases of proved damage, no other mechanisms are known to be implemented. It is expected that conflicts over groundwater will become frequent in the future, due to increasing water scarcity.

Investment in drinking water projects in the framework of the Millennium Development Goals will certainly stimulate beneficial use of groundwater, provided that those who plan the projects are aware of the opportunities offered by groundwater. Promoting the global priority for improving the status of drinking water supply by direct investments instead of by policies and regulations alone is undoubtedly a powerful contributor to enhancing beneficial use of groundwater.

Withdrawal of deep-seated groundwater, development of geothermal energy and a wide range of uses of the subsurface are expected to gain importance in the future and affect the allocation of groundwater and the benefits from its use. So far, groundwater governance has largely ignored these activities.

Finally, intergenerational allocation of groundwater is an issue that deserves attention in areas where aquifers are currently being depleted by intensive groundwater withdrawal. Currently, no plans are known that address this issue in sufficient detail.

6.4 Legal and institutional matters

Legislation and regulatory frameworks

Most countries have legislation on water or even specifically on groundwater. It captures the ideas, perceptions and knowledge available during the period of preparation; consequently, in many cases there is a need for updating legislation, in order to make the law consistent with modern views.

One of the legal issues that deserve more attention is groundwater ownership, or – more broadly – tenure. Unlimited entitlements to groundwater based on land ownership currently still prevail in many countries, defying the laws of nature and forming an obstacle to controlled exploitation of the groundwater resources.

A wide range of developments will require new or improved legal responses. This is, firstly, because environmental concerns and climate change are becoming more prominent. Next, there are increasing needs to measure water policy and legislation against human rights. In addition, new legal rules are needed to deal with the use of deep-seated aquifers and different other uses of the subsurface. In most countries these activities in the deeper domains of the subsurface are not regulated by water law but by mining law. Furthermore, there is a tendency towards more holistic approaches in groundwater resources management and governance. Legislation of interfering policy fields therefore needs to be made coherent.

International legislation on groundwater includes the Water Framework Directory of European Union and the Draft Articles of the Law on Transboundary Aquifers. The former – with its Groundwater Daughter Directive – has catalysed and intensified enormously the activities of member states related to groundwater quality monitoring and control. The latter (the Draft Articles) are non-binding, but may play an important role in guiding countries that are planning to draft international treaties with neighbouring countries on shared aquifers.

At the level of regulatory frameworks, permit systems are increasingly being challenged. This calls for analysis of the reasons of malfunctioning and perhaps also for new creative approaches to address scarcity.

Organizations and stakeholders

Government organizations in charge of assessing, monitoring and/or managing groundwater are widespread. They used to be part of entities in charge of irrigation or public water supply, but in recent decades there has been a tendency in many countries to separate water resources management from water use sector organizations. As a result, groundwater resources management (and often also assessment and monitoring) has been entrusted to sector-independent organizations, for example a special water resources management ministry or agency, instead of a ministry or agency in charge of public water supply or irrigation.

The capacity and effectiveness of these government organizations vary considerably. However, except for a number of developed wealthy countries, the general picture is that these organizations are usually understaffed and have insufficient budget to address the large number of challenges and problems related to groundwater.

Changing this for the better obviously requires action that puts groundwater high on the agenda of decision-makers.

At the local level, there is a long legacy of local institutions around groundwater sources, such as shared springs, dug wells and qanat systems. They used to function independently from government organizations, like the more recently emerged NGOs dedicated to groundwater projects in several countries. The effective involvement of stakeholders in groundwater resources management is, in most countries, non-existent or still in its infancy. Where it does exist, sector-related central government organizations (like ministries of irrigation, public water supply, or the environment, etc.), or related agencies, are often supposed to represent the stakeholders. Involvement of local stakeholders is still rare, with the exception of some countries where local water users associations have been established. There is still a long way to go before 'participation' (as defined as one of the characteristics of good groundwater governance) becomes a reality around the world.

6.5 Policies, strategies and operational activities

As a result of its specific characteristics, governance of groundwater is inherently more complicated than governance of surface water. Many of the impacts associated with emerging groundwater problems depend not only on the resource base and its use, but also on a much wider array of social, economic and environmental conditions. Therefore, these conditions have to be taken into consideration for effective groundwater resource management. Policies and strategies on groundwater, however, are in many countries still focused on groundwater as an extractable commodity, without considering the broader context. It will take commitment and time to make a transition, if this is opted for.

Recommended principles and considerations of 'good' groundwater governance are many, covering political, institutional, socio-cultural, economic and ecological aspects. Spatial and temporal contexts determine the applicability and potential success of the different governance paradigms (state-, market or collective action-driven) and management instruments.

7. How to improve the state of groundwater governance?

Generally, valid recipes for improving groundwater governance do not exist, given the large diversity in conditions around the globe. This diversity does not only relate to the current stage of groundwater governance in a particular area (ranging from non-existent to well-developed), but even more to differences in physical settings, socio-economic conditions, culture, political situations and other factors. Nevertheless, the steps outlined below are suggestions that may contribute to improving groundwater governance in a particular area. These suggestions are presented under five broad categories:

- Approaches to groundwater governance
- Information, awareness raising and communication
- Legal and institutional matters
- Stakeholder participation
- Anticipating the future.

Local institutions with a mandate for groundwater management have to make their own judgement which ones of the suggestions would be feasible and effective in their particular situation. Without in-depth inventory it is hard to tell which ones of the suggestions are likely to be most relevant, on a global level. Nevertheless, in the majority of cases, the impression exists that it is neither the technical nor legal instruments that form bottlenecks in groundwater governance. Instead, it is often perceived that the challenge lies in the process of getting all relevant parties to commit and co-operate towards a common goal.

7.1 Approaches to groundwater governance

Principles of good groundwater governance

In the endeavour to transform a given present situation into 'good groundwater governance' it will be helpful to start by analysing to what extent the general principles and considerations of good groundwater governance are already incorporated and which ones are not. The outcomes of this analysis will give guidance to enhance groundwater governance, subject to the feasibility of the envisaged improvements in the local context. These principles and considerations fall into four main sets of principles and considerations:

- *Political and institutional:* This includes accountability, representation, consistency, scalar match, institutional match, and institutional capacity to adapt to uncertainty and change. Groundwater is mostly a local issue and solutions need to fit institutionally and socio-culturally—recognising that paradigms and social constructs change over time.
- *Socio-cultural:* Deals with perceptions about groundwater, religious and spiritual traditions, social learning, social inclusion, ethics, multi-level/multi-scale/polycentric governance models.
- *Economic*: Here attention is required for the imperfection of price signals, the role of scarcity and groundwater-storage conditions, water-quality impacts, inadequate measurement of groundwater usage rates, the growing role of the private sector and public-private partnerships, and the importance of ability to pay. In addition, water prices may not fully reflect the costs of extraction, and rarely include third-party and environmental impacts of groundwater use. Economists often see market mechanisms as having potential to match demands with supplies, but the incidence of externalities related to the common-pool nature of groundwater should not be overlooked.
- *Ecological*: Focusing on physical characteristics that define movement, storage, attenuation rates and renewability. In addition, groundwater development may rival existing land uses. Groundwater systems can be considered as common-property resources, vulnerable to over-exploitation and/or under-management. Aquifers are to be valued not only for their provisioning services (for consumption, agriculture, or industry) but also for their environmental and ecosystem-supporting services.

Holistic approach

Groundwater management consists of sets of policies or decisions that impact groundwater use and protection. Opting for an integrated water resources management approach (IWRM) is a logical response to the close interaction between groundwater and surface water, and reflects a guiding governance principle fostering conjunctive management. However, there may be many decisions, public and private, that appear to fall outside the domain of 'water governance' but still affect the use and protection of the water resources. Examples are decisions related to land use, irrigation, energy development and agricultural subsidies. There is evidently scope for improving groundwater management if attempts are made to harmonise the policies of all these interfering fields, preferably by formal links between the processes to develop them.

Selection of management instruments and measures

Not all groundwater resources management instruments and implemented measures are effective in a given context. Their effectiveness depends on the local physical, institutional, economic and social conditions, but also on the way these measures are designed and implemented. In cases of poor results, it is therefore important to identify the reasons why and to analyse whether obstacles can be removed that prevent the measures from being effective. A typical example is the permit system for abstracting groundwater: in some countries it functions satisfactorily, in many others not at all.

Adaptation is a still a relatively underused but promising approach. In terms of measures it includes indirect management strategies that motivate users to adapt to local conditions (e.g. power pricing/rationing, crop price support, etc.), but it encompasses also adapting social and economic systems to groundwater conditions and changing socio-economic context for reducing or mitigating problems. Such measures attempt to adjust water demand to water availability (demand management), rather than supply to demand (supply management). In a more general sense, adaptation can also be chosen as a leading principle of strategies and planning. This results in *adaptive management* characterised by an incremental approach, which allows a step-wise adjustment of policy and measures on the basis of observed impacts.

Conjunctive management of groundwater and surface water has the potential to contribute in the future much more than at present to good groundwater governance. This includes 'managed aquifer recharge' (MAR) as a prominent measure. Groundwater also still has large unused potential for developing geothermal energy and for improving domestic water supply in areas where this is still deficient.

Unequivocal 'best measures' for groundwater resources management do not exist. Which measures would be most effective in a particular case depends on the local physical, institutional, economic and social conditions. Given the complexity of groundwater and its context, measures should not be selected on an *ad-hoc* basis and in isolation. The development of a wider policy perspective is essential to frame 'good groundwater governance'.

7.2 Information, awareness-raising and communication

Information and knowledge

Information and knowledge regarding local conditions – i.e. the baseline characterisation of the groundwater resources and of the local socio-economic context – are essential inputs to good groundwater governance. Without them, groundwater governance has no real content, as they are indispensable for proper diagnostics, development of rational strategies and assessing the impacts of implemented measures. It is thus vital that governments consolidate a sufficient level of information and knowledge on groundwater. In particular, much more attention than is presently given is required for monitoring the most relevant time-dependent variables related to groundwater state, groundwater withdrawal and also the benefits and side-effects of groundwater withdrawal.

Carrying out projects for collecting data and information is not enough. Responsibility for developing groundwater information and knowledge should be vested in special national agencies (e.g. geological surveys) that are dedicated to this task and ensure its continuity and objectivity. Such agencies should develop user-friendly tools and procedures for the retrieval of data and information.

Awareness raising and communication

Except for groundwater professionals, most people are unfamiliar with groundwater systems, the opportunities they offer and the problems that are to be solved or controlled. It is therefore not realistic to assume that politicians and other decision-makers are motivated to put groundwater high on their agendas and to make budgets and other means available for groundwater governance, unless they are made fully aware of what is at stake and of the benefits their contributions may produce. Likewise, without correctly understanding groundwater systems and their context, many stakeholders in groundwater only react to problems and are neither motivated nor capable of cooperating pro-actively. Therefore, developing awareness on groundwater among stakeholders is an essential component of good groundwater governance.

Awareness-raising is also needed because all partners in groundwater should understand each other properly. This means that groundwater specialists and planners should engage with policy makers in order to understand their objectives, concerns, priorities and constraints. They should also make efforts to identify and understand perceptions of stakeholders, their dependency on groundwater, their preferences and problems they experience.

Reaching an effective level of awareness is a first step towards structural communication between decision-makers, planners, groundwater specialists and stakeholders. This communication is essential to build confidence among the parties involved, to ensure that all relevant aspects and considerations are addressed in a balanced way, and to agree on solutions in case of differences of opinion or conflicts of interests.

7.3 Legal and institutional matters

Policy coherence across sectors

Good groundwater governance implies that the laws related to groundwater allow for coherence between the policies for groundwater and those in related fields such as surface water management, land use planning and environmental protection. They should also attempt to harmonise groundwater governance with the different categories of use of the subsurface space and resources that come under other laws and institutions, and ensure that they assign clear mandates to the organizations in charge of enforcing groundwater management measures.

Adapting laws

Where laws related to groundwater no longer reflect the current conditions or views, these should be updated. Special care is needed to ensure that they assign clear mandates to the organizations in charge of enforcing groundwater management measures. Private groundwater ownership and user rights might be perceived in some cases as posing constraints to good groundwater governance. In such cases, it might become necessary to amend the law to better protect the common good. In cases where state ownership has been accepted, but introduced permit systems for groundwater withdrawal are not functioning properly, the reasons of this malfunctioning have to be explored in order to improve these systems or replace them by other demand management instruments.

An institutional home for groundwater

In many countries, the bottleneck hindering adequate groundwater management is probably lack of powerful, effectively operating organizations in charge of groundwater. If a real 'institutional home' for groundwater is missing, then it should be established – either as one organization or in the form of a few, each with its own clearly defined tasks, such as assessment and monitoring, policy development and planning, and operational management. Crucial requirements for such organizations are clear mandates, adequate budgets and sufficient staff that are not only well trained but also capable of cooperating with the different actors in groundwater governance.

7.4 Stakeholder participation

Empirical evidence suggests that stakeholder participation can be an effective contribution to achieving good groundwater management. There is a great diversity among participatory approaches to groundwater management: they range from informing or consulting local stakeholders to fully delegated local groundwater management. Despite its generally good potential, participation may also have its drawbacks. For example, there is a risk that participation may reflect or even increase existing inequalities, and participation may in some cases cause long delays in decision-making and planning.

As groundwater problems intensify, incentives for participation and collective local management grow among the local population. Cooperation by partnerships between local stakeholders and dedicated public agencies is usually an effective approach, but it requires long-term commitment on both sides.

Experience shows that it is important to build on existing social capital, promote equity and inclusion, start in areas of good potential, go step-by-step, learn lessons and adapt. There is a wide range of methods and tools available to support stakeholder participation.

7.5 Anticipating the future: demography, climate change, new frontiers, etc.

Good groundwater governance takes into account that the world around us is not static but subject to continuous change. Consequently, drivers of change should be identified and assessed, in order to use most realistic estimates of autonomous trends as boundary conditions to any predicted future.

Besides the more classical demographic trends, commonplace in water resources planning and management, two issues deserve special attention: climate change and new frontiers in the use of subsurface space and resources.

Climate change is still subject to many uncertainties, but this should not prevent countries from building preparedness. Even under uncertain predictions of local climate change, it is already possible to provisionally explore impacts, to identify the most vulnerable areas and look for options for mitigation and adaptation. The role of groundwater management may be, on the one hand, to identify groundwater systems and functions at risk and designing measures in response. On the other hand, in an integrated water resources management context, it can promote the use of groundwater as a buffer to mitigate the water scarcity problems that may affect surface water and its functions most of all. International organizations may contribute by carrying out projects in developing countries, resulting in valuable lessons and experiences.

Use of the subsurface space and its resources other than groundwater are still beyond the scope of common groundwater resources management and groundwater governance endeavours. Good groundwater governance should require that the increasing intensity of these activities and their interference with groundwater are no longer ignored.

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Trends in Groundwater Pollution: Loss of Groundwater Quality and Related Services

Digest

Most groundwater governance issues refer to water quantity in arid and semi-arid areas, but quality issues are as or more important once water is made available. Groundwater is often of good to reasonable chemical quality for most uses and free of disease-producing biological components, provided springs are well protected and wells adequately constructed and maintained, what is not always the case, especially not in rural areas and in developing countries.

There are exceptions to the often good quality. This is due to excessive salinity of natural origin, especially in arid areas, which is often the result of climatic effects. Poor quality may be also due to excessive contents of some natural solutes, some of them affecting human health, such as arsenic and fluoride, as is the case in large areas of Southern Asia and of Central and South America.

Human activities may induce or produce some serious groundwater quality deterioration (contamination) through different processes and with variable intensity and impact on health. Some involve the introduction of salinity and deleterious substances – pollution – from sewage infiltration, disposal of wastes, and leakages. But other processes indirectly deteriorate groundwater quality by affecting groundwater flow pattern – facilitating the penetration of sea, surface and ground saline and contaminated water – or polluting recharge water as a consequence of distributed land-use activities such as agriculture, animal raising, increasing recharge after deforestation in areas containing saline water in the unsaturated zone, urbanization and mining activities. The impact of land-use changes is often not easily recognized since specific pollutants are not clearly involved or identified, and the activity is not directly related to water resources development. Agriculture is often an important polluter, responsible for groundwater quality degradation, whose impact is increased by the widespread use of fertilizers –especially nitrates – and pesticides, in rain-fed farming and especially in irrigated farming. Also it is feedstock in intensive exploitations. Nitrate-derived pollution is currently an important and serious concern in many areas, in most countries.

In many areas of the world there is a sustained trend to groundwater quality deterioration due to increasing aquifer development and human activities applying every time more chemicals. This is a common situation in agricultural areas and in urban and peri-urban areas. Often mountainous and forest areas are still close to pristine conditions, except for increased air-borne pollution from far away areas. This deterioration trend is not always observed and recognized since there is a delay – sometimes a long delay – in the transfer of contaminants through the unsaturated zone, vertical mixing with water in the aquifer dilutes newly arrived contaminants and thus masking their presence for some time, and wells may be far from the newly contaminated areas. Groundwater transfer rate is slow to very slow, and still slower for groundwater-reactive – sorbed – contaminants. The delay may be from months to centuries, depending on local circumstances.

An unobserved trend to groundwater quality degradation in springs and wells does not necessarily mean that the aquifer groundwater quality is not deteriorating in the whole, but only that polluted water already in the ground is not detected since it is still in the unsaturated zone, or is moving from the pollution source, or it is far from the place where water is obtained or monitored. This also means that when a pollution source is detected the volume of groundwater and terrain affected may be large. Correcting and suppressing the pollution source is not necessarily accompanied by a groundwater quality improvement, especially for distributed (non-point) ones; the deterioration trend may continue for some time, even a long time. This is a serious handicap for aquifer protection actions, which may demand important costs and technical and difficult political decisions to produce changes for a future that is too difficult to consider when compared with normal human behaviour times.

Pollutants may be degraded in the soil, the unsaturated zone, and the saturated zone due to different physico-chemical and bio-chemical processes, but many of them may not decay or persist a very long time. This depends on local conditions. Some pollutants that seem to be decaying may be simply retarded by sorption or diffusion into low-permeability heterogeneities, but do not disappear, and are slowly released later on. This is very relevant to aquifer restoration and explains how groundwater quality recovery is a very long, tricky, and highly costly action, if feasible at all.

Typical situations of groundwater quality problems and trends of quality deterioration can be singled out, although there are no simple situations. Each case has its own characteristics to be taken into account. There are conspicuous differences between fine-grained porous, homogeneous aquifers and karstic and fractured aquifers, but even in these cases the actual situation depends on the vertical sequence of layers, the existence of soil, the thickness of the unsaturated zone, the vegetation cover, how groundwater is abstracted, recharge rate, the distribution of discharge areas, etc. Thus, to understand and manage groundwater quality and to know present and future trends, what is firstly needed is a good conceptual model of aquifer behaviour that considers flow and mass transport. It is the basis for later calculations, from simple ones to more or less complex mathematical models. Methods to be applied have to be tailored to each actual situation, their relevance to water supply, the use of water, and the complexity, taking into account data availability and what existing regulations and society ask for.

Groundwater quality is an important issue in groundwater governance, that may suffer from some important constraints, such as insufficient knowledge of the aquifer and the processes, lack of trained staff to understand correctly the facts, and poor sensitivity of people about quality issues until degradation is advanced, often too advanced; then aquifer and water quality management is difficult, costly, and politically unrewarding due to the often slow and long-delayed achievements, if any, after important investments and socially unpalatable actions. Groundwater policies aimed at quality are usually the most difficult and the more controversial ones, since groundwater is generally considered like an almost free-access common good, and this is difficult to root out, if feasible, in exchange of adequate regulation and agreed common action. This is currently controversial.

Direct technical management action for governance involve evaluating aquifer vulnerability to pollutants – a not simple and sometimes controversial concept – establishing protection areas, and banning, limiting, or regulating the use of some potential pollutants. But results are often doubtful and socially contested. Current practical experience is scarce and poorly documented. However, direct management through legislation and norms are needed to some extent, but they should be accompanied by effective enforcement. This effective enforcement is often a big failure in many areas since neither the rules are suited – they do not respond to the real situation – nor the means to enforce them are available, and often there is not the political will to support them due the rules being unpopular or due to corruption.

Indirect management action for governance is often effective, although limited experience is currently available. This involves adequate institutions in the government – supported by laws and rules as part of the institutions, as well as the correct application of the subsidiarity principle – and in the civil society, something that is often inexistent or weak in many countries, and also suppressed when political action goes too far. Also, the involvement – co-operation and shared responsibility – of groundwater users and other stakeholders is needed and constitutes a highly favourable step, which should include those entities representing the environment. Actually there is little experience on this involvement, but there are some encouraging initiatives in some countries, adapted to their legal and social circumstances, with different degree of success and an often slow pace of introduction.

In any case, governance needs knowledge and this knowledge has to be based on adequate monitoring and making the data available to all interested parts and stakeholders.
Although there is a big consensus that correcting groundwater quality degradation is much more expensive than prevention, this has to be evaluated in terms of the discount rate to be applied to future investments. A low rate is in favour of protection but a high rate favours transferring the problem to future generations, which are assumed to be endowed with improved technological means and more economic resources than the present one. These two extremes should by tamed by other aspects and the actual economic and social situation – expansion or recession – when decisions are made. This changes and fluctuates along time and with them the policies. However, groundwater quality protection still continues to be an accepted policy.

Contaminated aquifers should not be left aside since they contribute water to other water bodies and their water can be put into beneficial use after adequate treatment, although often at high cost, which often can be only paid by urban supply to relatively rich areas, to some factories, and by highly profitable, intensive agricultural developments.

The trend to dislocate groundwater polluting activities – including agriculture – to other countries to avoid local groundwater pollution problems, and then import the products from abroad – they include virtual water– is part of world water governance since these involve global trade, virtual water import, and also “virtual” pollution transfer to third countries.

The prospect of groundwater quality, as above said, is often a trend towards some quality degradation – sometimes serious – by increasing salinity – which includes sea water intrusion in coastal areas – nitrate build-up, deleterious organic compounds – hydrocarbons, chlorinated solvents, pesticides – and in urban and peri-urban areas also an increase in “emerging” contaminants at very low level – pharmaceuticals for humans and animals, estrogens, endocrine disruptive chemicals, cosmetics, legal and illegal drugs – whose effect is poorly known in the long run.

This prospect asks for strengthened action to preserve groundwater quality to a reasonable extent which should be compatible with current economic and social circumstances (it should not stop necessary current development) and this, besides some technical and serious enforceable legal action, needs adequate and effective action from government levels and of the civil society institutions, and also the involvement, co-operation and co-responsibility of groundwater developers, users and stakeholders, including those related to environment preservation.

Studies about climatic effects on groundwater quality are scarce. The large climate fluctuations in the past are related to some current situations, especially those related to the last glaciation that ended about 10,000 years ago. Some currently used groundwater resources are palaeowaters – recharged under more favourable climatic conditions than current ones –, but other another type of palaeowaters are relict saline groundwater – the result of drier periods –, formed either directly *in situ* or indirectly, through dissolution of minerals from salt deposits. Similarly, future climatic change may affect groundwater quality according to how recharge will be modified, since the atmospheric transport of air-borne salts is assumed less variable if the distance to the sea does not vary. This change of recharge rate not only depends on annual rainfall, but on its distribution and how the vegetation cover will change, a quite delayed effect. In arid and semi–arid areas, extreme events and their intensity may be more important than change in annual rainfall. However, land use changes may have a greater effect on recharge and groundwater quality than climatic change in many areas in the world.

Thematic Paper 1

TRENDS IN GROUNDWATER POLLUTION: LOSS OF GROUNDWATER QUALITY & RELATED SERVICES

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Acronyms

EC	European Community
EEC	European Economic Community
EPA	US Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environment Facility
IAH	International Association of Hydrogeologists
IHP	International Hydrological Programme
IWRM	Integrated Water Resources Management
PHI	Programme International Hydrologique
USA	United States of America
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

The following chemical symbols have been used for dissolved substances (mostly ions):

As, AS(V)	Arsenic, arsenic at valence +5
Ca	Calcium
Cl	Chloride
CO2	Carbon dioxide
F	Fluor, as fluorine
Fe, Fe(II)	Iron, reduced iron (valence +2)
Mg	Magnesium
Mn	Manganese
Na	Sodium
NH4	Ammonia
NO3	Nitrate
SO_4	Sulphate

1 Introduction

The purpose of this Thematic Paper is to review the trends in groundwater quality and pollution, taking into account the physical, environmental, institutional and social actors involved in groundwater quality governance. The final goal is to diagnose historical and current issues related to groundwater use under the threat of pollution, and to identify prospects for improved and sustainable aquifer governance through prevention and mitigation of the factors that may impact water quality. It is aimed at the macro-view level, based on existing experience from real cases.

With the relatively recent development of centrifugal pumps, mechanized drilling means and energy accessibility, as explained in Technical Paper 8, groundwater is seen as an easily-developable water resource, invisible to people and lacking in social experience on its use as a common good. It is linked to surface water, and is essential for nature and its services (Llamas and Custodio, 2003). Groundwater governance refers to the sustainable and efficient use of this key resource, which is essential for drinking-water supply, food production, human development and the environment (Ragone *et al.*, 2007; Bocanegra *et al.*, 2005), as well as for the resolution of conflicting situations. A working definition is given in Box 1.

Box 1: A working definition of groundwater governance

Groundwater governance is the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck, 2007: Dictionary and Introduction to Global Environmental Governance).

A technical tool for groundwater governance is integrated water resources management (IWRM), which consists in the coordinated development of water, land and related resources to maximize social and economic welfare without compromising the sustainability of vital ecosystems, as explained in Technical Paper 5 of this series. Government officials, politicians and people in general must be conscious of the state of the resource they are using in order to tailor timely solutions suited to local circumstances. Unfortunately, before action is taken, major deterioration or depletion often has to occur in many aquifers. Water quality requires particular attention as its impairment is hidden, slow and delayed.

Within the concept of groundwater governance, aspects related to quantity and quality of the resource may be distinguished. Groundwater quality governance is often not of primary interest in situations where water quantity is a concern. This explains why groundwater quality protection is still poorly developed, although its importance is certainly growing. In fact, in semi-arid and arid countries in particular, once quantity needs are satisfied, quality issues become progressively more important.

The poor development of groundwater quality governance largely depends on the difficultly to assess water quality, compared to water quantity. This is due to the great number of components and factors involved in water quality assessment, as well as to inconsistencies in the knowledge base, which is therefore often subject to interpretation. Even a satisfactory and widely accepted water quality index is unlikely to be fully reliable.

2 Basics Aspects of Groundwater and its Quality

Groundwater development is relatively recent and rapidly evolving (Figure 1). It mostly started during the 20th century and, in many countries, only a few decades ago. Due to intensive groundwater development, aquifer functioning has been greatly modified (Llamas and Custodio, 2003; Custodio *et al.*, 2005) and needs management to become sustainable (López Gun *et al.*, 2011). This development implies that direct and indirect benefits and costs are produced and often involves an impact on groundwater quality.

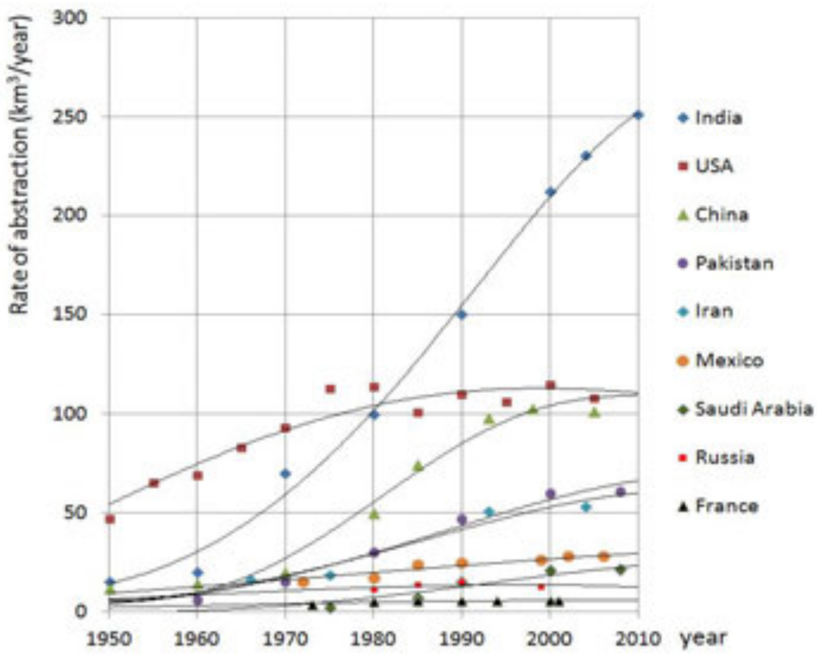


Figure 1. Evolution of groundwater abstraction since 1950 for some countries with intensive groundwater development (after Margat and van der Gun, 2013).
While in some countries groundwater abstraction is attaining a steady state or even decreasing as they are more efficient using water and rely on integrated water resources systems, others are still in the early stages of fast development. Abstraction is given in km^3*/year.*

Intensive aquifer use, in many cases, and especially in large confined aquifers, may involve the transient depletion of groundwater reserves. In some areas of the world, continuous and unrestricted use of groundwater reserves – known as "water mining" – has led to the physical depletion of aquifers, water quality impairment and the increase of abstraction costs (Foster, 1991; Foster and Loucks, 2006; Custodio 2010a).

For a correct evaluation of groundwater resources, a validated conceptual model on how the aquifer system functions is needed, including mass transport as the basis for water quality assessment. Also, information concerning aquifer recharge is very important, even if it is often rather uncertain. These are key issues for groundwater governance that must be addressed to control groundwater development in a coherent and consistent manner.

Three main aspects of groundwater governance have been identified (Hydrogeology Journal, 2005):

1) its role in nature and the environmental services it provides;
2) its quantity to supply human needs; and
3) its quality with respect to human uses, including productive activities, and to the environment.

In the European Water Framework Directive (Directive 2000/60/EC of 23 October 2000 establishing a framework for the Community action in the field of water policy), which aims at preserving the quality of the environment, water quality issues are the backbone of governance. As groundwater is mostly used for drinking-water supply, quality issues are particularly important. This happens in relatively rich urban areas, where in some cases (as in Germany) good quality groundwater without further treatment is wanted for urban supply. In the European Union (EU), the dependence on groundwater for drinking-water supply varies between 98 percent in Denmark, to about 50 percent in Sweden, and only 20 percent in Spain. Even in countries with low groundwater use, some areas and many of the small towns are often fully dependent on groundwater. In poor areas, the lack of infrastructures makes quantity issues the main concern for governance, except if serious threats to health appear due to the presence of natural hazardous substances and serious pollution.

In the arid and semi-arid regions, irrigation is often mainly based on groundwater use, and water scarcity makes water quantity a main issue, linked to increasing water cost, depletion of spring flow and river base flow, decrease of wetland areas, and in some cases land subsidence problems. In integrated water systems, groundwater provides the needed water reserve where water shortage due to droughts is a main concern (Estrela and Vargas, 2012). Thus, water quality issues are often of secondary importance in aquifer governance, except in certain coastal aquifers, intensively irrigated agricultural areas, peri-urban areas that depend on local water resources for human supply, and in general where natural groundwater contain solutes recognized as a health problem, such as arsenic (As) and fluor (F). See Boxes 2 and 3.

However, groundwater quality is deteriorating worldwide and a growing concern, often the result of past action. This means that in many areas, currently poorly addressed quality issues will become soon a dominant issue for groundwater governance. Unfortunately, existing experience is short and patchy, and has an important local component. Governance of groundwater quality is at its early stages and often considered as 'an issue for the future' in many countries. In addition, it is not easy to show groundwater quality evolution, worldwide or at regional level, not only due to data scarcity but also to the difficulty of using an index that is able to reflect the different points of view. The evolution on a chemical characteristic at a given point does not always show the general trends.

Poor groundwater quality is due to the presence of contaminants. The term 'contamination' is considered here in broad sense, including salinity, physico-chemical characteristics, inconvenient solutes at very different concentrations, biological components, radioactivity and temperature. Groundwater contaminants may be: (i) of natural origin, induced by aquifer exploitation; (ii) introduced as a result of human activity; or (iii) a combination of the two. Only contamination resulting as a direct consequence of human activity is here considered as pollution.

The main causes of groundwater pollution that should be tackled in groundwater governance arrangements, both at large and at small scale, are:

a) land-use activities, part of which are unrelated to groundwater development;
b) groundwater development, including the means of groundwater abstraction, such as well and borehole construction, operation and maintenance;
c) groundwater–surface water relationships, as in many cases groundwater contamination comes from surface-water infiltration, including seawater in coastal areas, saline lake water and polluted river water;
d) inter-aquifer leakage.

Necessary components of groundwater quality governance are laws, norms, institutions, direct groundwater users and other stakeholders that have interests in groundwater-related issues, such as the environment and its ecological services, surface water, springs and agriculture. Assessment and action depend on adequate monitoring and good understanding of aquifer-system functioning and behaviour, reflected in a validated aquifer-system conceptual model and supported, when appropriate, by numerical modelling and hydro-geochemical and isotopic studies.

Part 1: Baseline

3 Naturally-Occurring Groundwater Quality

3.1 Groundwater composition and salinity

Groundwater is generally fresh under natural conditions, although not always necessarily of good chemical quality. Chemical groundwater composition of recent groundwater is the result of climate–soil processes and lithological influences (Figure 2). Climate-soil processes dominate in arid areas, and lithological influences do in more humid environments. The mineral concentration in water due to atmospheric deposition is increased by evapo-concentration – the concentration of solutes by water evapotranspiration – in the soil. The more arid the climate is and the higher the capacity of soil to hold water is, the greater evapo-concentration is. What remains will be converted into groundwater recharge, which incorporates soil CO_2 from root plant respiration and organic matter decay by oxidation. This favours the dissolution of soil and rock minerals.

These well-known processes (Appelo and Postma, 1993; Custodio and Llamas, 1976) control groundwater quality baseline or background (Edmunds and Shand, 2008; Custodio and Manzano, 2007). Marine components dominate generally near the seacoast. Inland-wards, where the marine influence decreases, terrestrial components and anthropogenic influences tend to dominate, particularly in more arid areas. Anthropogenic influences may have an important impact on water quality in and near populated areas, and below agricultural land in which agrochemicals are applied, especially when intensively cultivated under irrigation.

Recharged water may suffer other geochemical processes in the ground (Figure 3). Since directly soluble minerals are rare in well-leached rocks, in an oxidizing ambient groundwater percolation (in-transit recharge) will be little modified afterwards, except for the possible incorporation of deep geogenic CO_2 in recent volcanic areas and the resulting reactions, ion exchange processes when groundwater is displacing or displaced by water with a different ion composition, and some redox (reduction-oxidation) processes affecting solutes such as sulphate (SO_4), nitrate (NO_3), and dissolved iron (Fe), manganese (Mn) and arsenic (As), among others.

A consequence of the above is natural groundwater quality zoning, depending mostly on climate and distance from the seacoast, shaped by local lithology. Groundwater recharge may be fresh in continental areas, even in arid areas, when continental contribution is small, but rather saline near the coast, even in the absence of direct seawater intrusion. The effect is clearly seen in small, high elevation, variable climate islands, such as the Canaries and Cape Verde (Figure 4).

Soluble saline components may be found in still unleached, recent marine or saline lake sediments, and where still unleached evaporite salts are found in the rocks, most often gypsum, but also halides from closed-basins formations or forming part of local rocks. Many different circumstances are possible.

Brackish and saline groundwater is relatively frequent in deep aquifers, especially in slowly renovating, confined aquifers, and also as a consequence of recharge in arid environments. In coastal areas, brackish and saline groundwater is the result of natural seawater intrusion in thick, permeable and relatively poorly recharged aquifers, and the mixing with fresh groundwater in upper layers (UNESCO–PHI, 1986). In small permeable islands a fresh-brackish groundwater lens may be partly or fully floating on a continuous deep groundwater layer of seawater, with a more or less thick mixing zone between them (UNESCO–PHI, 1991). In coastal areas and around large saline lakes and inner seas, salinity can be also the result of periodical land flooding during heavy storms –very acute in tsunami events –, of wind-driven seawater spray or of intense evaporation from surface and shallow saline water bodies.

Soil water and groundwater interaction with sediments and rocks, out of the most common soluble minerals, involve reactions such as the hydrolysis of carbonates and silicates. This may incorporate solutes that may affect groundwater quality for the intended uses, and especially for drinking purposes. See Table 1 for comments on some of them.

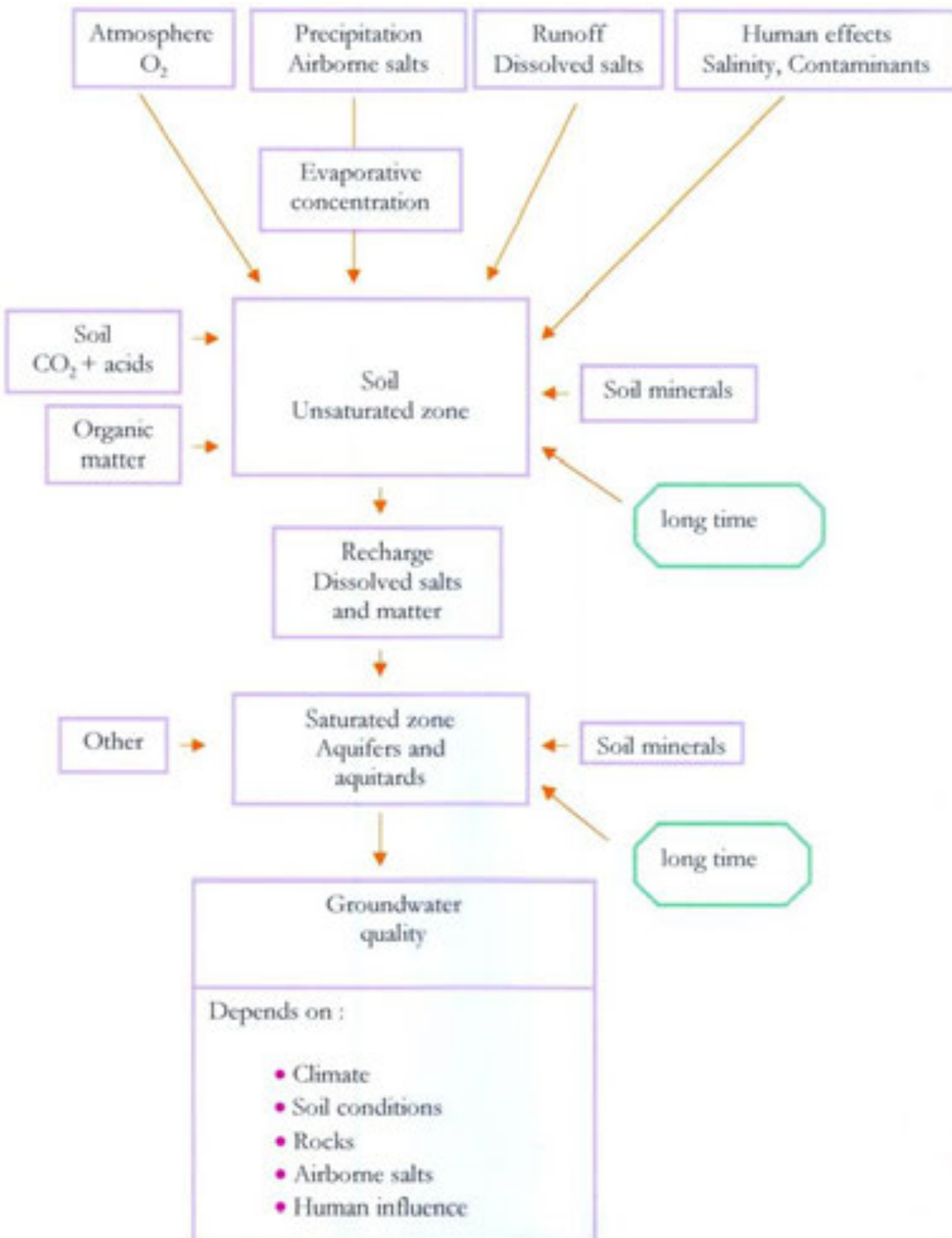


Figure 2. Genesis of groundwater chemical composition due to rainfall diffuse recharge.

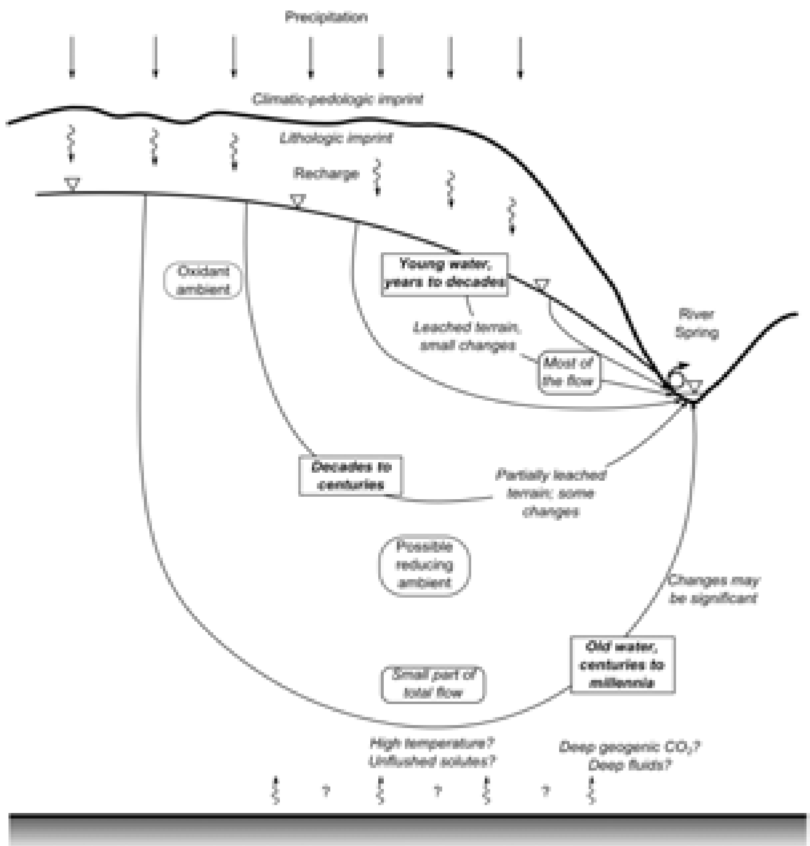


Figure 3. Schematic, highly simplified aquifer flow pattern in a thick water-table aquifer between an extended recharge area and the concentrated discharge along a valley.

Circumstances and possible groundwater ages are indicated, although they may vary largely according to size, recharge and aquifer characteristics.

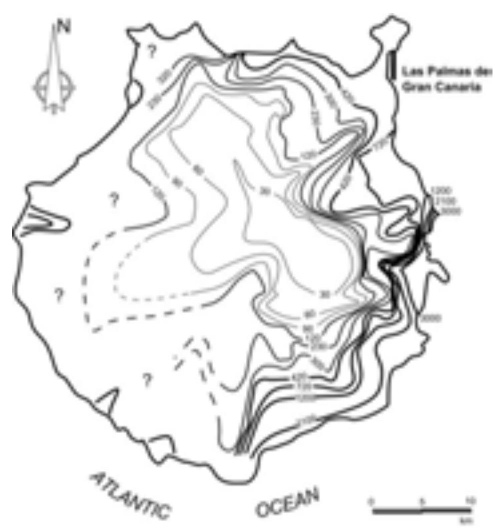


Figure 4. Groundwater quality changes as reflected in the chloride content, in mg/L, in the upper part of the main saturated body of Gran Canaria Island (Canary Islands, Spain), 1500 km^2 in surface area and 1985 m altitude. *Increasing Cl reflects the rapid decrease of recharge and the increased atmospheric Cl deposition when going from the highlands toward the coast. Fast Cl changes reflect deep geological boundaries (after Custodio, 1989).*

Table 1. Some inconvenient natural groundwater components that may be of natural origin

Component	Origin	Problems	Comments
Salinity	Aridity Closeness to the sea coast Relict marine water Deep-seated old saline groundwater	Affects potability Impairs urban and industrial use Affects crop yield in irrigated areas	Treatable through expensive desalination processes High salinity makes water useless
Hardness	Rock dissolution	Encrustations	Treatable at a cost
High sodium–bicarbonate	Deep CO_2 contribution in tectonically active and volcanic areas	Poor for drinking purposes. Risk of soil alkalinisation in irrigated areas	Not easily treatable
Fluoride	From rocks, especially acidic volcanics and dispersed volcanic ash when water hardness is low	Affects health (bone and teeth)	A serious problem in the Argentinean Pampas, Chile, Mexico, India, Pakistan, the East African Rift, some volcanic islands (Tenerife)
Iron	Mineral iron dissolution in acidic and reducing environments	Affects potability. Produce stains, encrustations and precipitates. Water becomes yellowish when oxidized	Easy to treat, at a cost
Manganese	Mineral manganese dissolution in acidic and reducing environments	Affects drinkability Produces black stains and precipitates, with some retardation	Easy to treat, at a higher cost than iron treatment
Arsenic	Sediments and rocks Dissolved under some chemical circumstances, not always well understood	Affects health Old limit of 50 μ/L has been lowered to 10 μ/L	A serious problem over large areas of Bangladesh, East India, Northern China, Argentina, Mexico
Boron	Some minerals and volcanic activity Desorption from fine marine sediments	Affects health at around 1 mg/L Detrimental to plants	

Pathogenic components – bacteria and viruses – are rarely of natural origin in groundwater, since they are subjected to highly hostile conditions in the ground, where they cannot reproduce and they eventually decay. Thus, natural uncontaminated groundwater is pathogen-free, except in special situations, such as when there is a fast penetration from the surface or when the residence time of water in the ground is short, as in karst aquifers, large fissures and shallow coarse gravel formations, especially when soil and low permeability sediments do not form a continuous cover that protects groundwater against direct infiltration from the surface (Goodfrey and Smith, 2005). Pathogenic bacteria and viruses may survive a few weeks to a few months in the ground, although some reports indicate up to one-year survival under favourable conditions. Generally they move slower –often much slower– than groundwater does, since they are strongly sorbed, and thus, before decaying, they spread a short distance – a few metres at most – in soil and fine-grained aquifers, except for coarse gravels and large fissures and conduits, where they may move away hundreds of metres.

Box 2: Groundwater quality governance in presence of high arsenic concentrations

Arsenic is widely dispersed in rocks and sediments. Its hydrogeochemical behaviour is complex and depends among other factors on ambient redox potential. Under reducing conditions it is held in sulphides, and under oxidant conditions it is retained in iron and manganese oxides and oxihydroxides. It may be released if sulphide and organic-rich sediments are exposed to oxygen, as when recent oxygen-carrying water penetrates deep formations or when air enters formerly saturated formations due to the lowering of the water table by groundwater development or drainage. It may be also released when polluted water carrying reactive organic matter produces a reducing ambient in oxidized sediments.

Thus, arsenic in groundwater is often of natural origin or the result of aquifer development. Its presence, especially at the higher oxidation state (As(V)), is a serious health concern for continuous exposal to it, and the medical experience has been in favour of lowering the former limit of 50 μg/L to 10 μg/L. This, however, has rendered large volumes of groundwater unsuitable for drinking purposes without costly treatment, which is often unaffordable in poor areas, or without blending with other sources of water, often a challenging task.

Well-known areas subject to excess As in groundwater are in Bangladesh, West Bengal (India) and the "pampas" of Argentina. Important research efforts have been carried out to know how and when As is present (see Smedley and Kinnibourgh, 2002).

Groundwater quality governance in these cases needs suited actions. Drilling shallower or deeper wells may avoid the problem for some time, but this solution is costly, needs good detailed monitoring of the concentration of supply wells and may be economically unaffordable in poor areas when deep wells are needed. Careful mapping may help in identifying areas in which hydrogeological conditions are not favourable for dissolution (Biswas *et al.*, 2012), but current experience in this field is still insufficient. This has been the result of two decades of studies in Bangladesh and West Bengal, in the vast deltaic areas. In the Argentine "pampas" (very flat land), most efforts have been directed to identify areas of current active recharge or where enhanced recharge is engineered. In those areas, shallow water bodies with low arsenic content may form. In any case the help of local authorities and local sanitary and pharmacies is important for control.

Figure B2-1 shows the global distribution.

Figure B2-1. World distribution of major reported problems of arsenic content in groundwater at concentrations higher than 50 μg/L (Smedley, 2008; Margat and van der Gun, 2013).

Box 3: Groundwater quality governance in presence of fluoride contents

The origin the fluoride (F), mostly natural, is not always clear, but in general is related to the existence of F–rich sediments with Ca–poor groundwater. These sediments are mostly of acidic and intermediate volcanic origin in subducting areas of the Earth crust, such as that in the western side of the Americas or in eastern Asia, or caused by volcanic activity related to very evolved magmatic chambers, as is the case of Tenerife, or in areas of the African Rift in Ethiopia, Somalia and Tanzania. Acidic volcanic ashes often have high F content, which are spread over large, far away areas, and are incorporated into other sediments, as is the case of large areas in Argentina and Bolivia.

Fluoride is needed in drinking water for healthy teeth and bones but an excess has a counter effect. Recommended values vary between 0.5 mg/L and 1 mg/L. Deficits are sometimes corrected by fluoride addition to drinking water – not always a well–accepted practice –, dietary habits or the use of fluoride-containing toothpaste. The excess is difficult to deal with although this may be done through physic-chemical treatment, at a cost that only relatively rich areas can pay, as is the case of Tenerife, in the Canary Islands, Spain. In other areas of the world, as in Mexico, Argentina, Bolivia, Chile and Peru, people living in poor areas may clearly show the detrimental effect of an excess of fluoride, at times up to several mg/L.

When the cost of water treatment to reduce F content is not affordable, one solution is selecting low F groundwater sources in the area for drinking purposes. Some wells or water galleries have to be discarded, often yielding sodium-bicarbonate water in CO_2-rich areas of endogenic origin. This means locating areas where groundwater renewal is fast, limiting penetration into the aquifer and promoting the use of rainwater collected in cisterns. In Mexico, drinking bottled water and refreshments imported from other areas is currently quite developed.

In figure B3-1 the global distribution of F is shown.

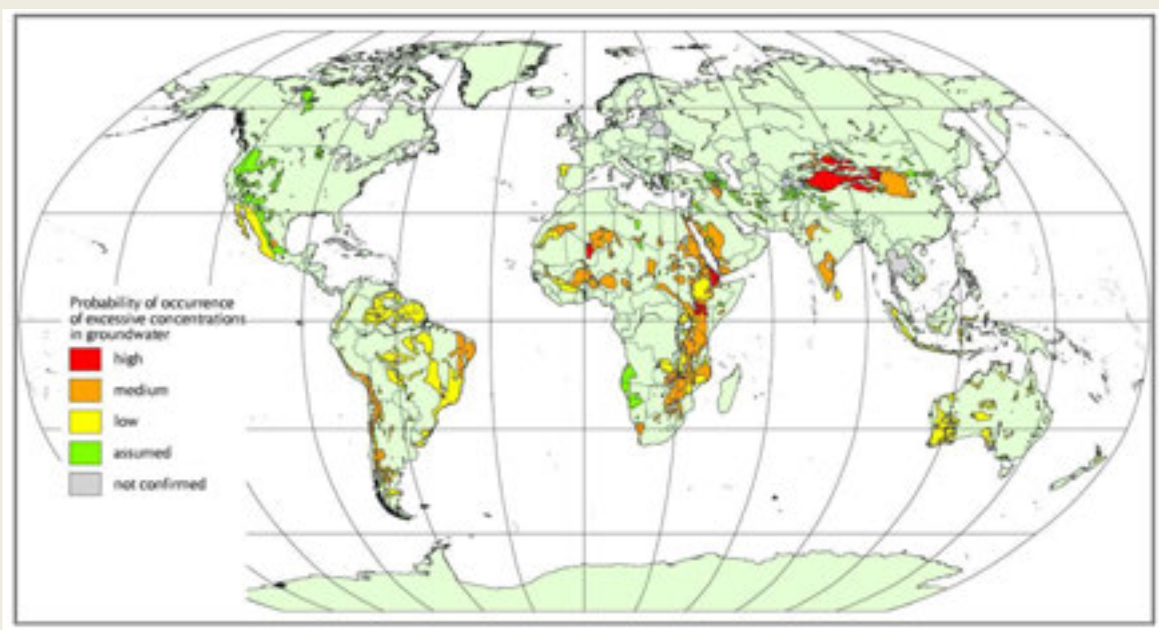


Figure B3-1. World distribution of major reported occurrence of high fluoride contents in groundwater, above drinking water standards (after Vasak et al., 2008; Margat and van der Gun, 2013).

3.2 Groundwater quality and tolerance

Natural groundwater quality is important for potable water but also for agriculture and other human economic activities, as well as for the environment and the services it provides. A groundwater discharge area may be linked to a characteristic habitat, and most living species are sensitive to water quality and its changes, both in land and in littoral waters.

Plants have a tolerance limit to salinity of the water that is available to their roots. When irrigation-water salinity increases, an increased irrigation water depth (volume per unit surface) is needed to keep salinity at the roots and flush out the excess of salts. Otherwise crop yield decreases. Moreover, the soil must remain aerated. When applied water has an excess of sodium ion (Na) over earth–alkaline ions (Ca+Mg), as happens for the sodium- bicarbonate-rich waters found in CO_2-rich volcanic areas, the soil becomes less permeable and gets easily saturated; this hinders aeration, hence the plant is stressed and may die. Also when boron concentration in soil water is high, plants – especially the leaves – are poisoned. Water quality effects in irrigated agriculture depend on crop, irrigation frequency and depth, soil characteristics and the presence of some inconvenient components. Salinity tolerance depends on how soil water characteristics can be controlled. Effects need some time to develop and thus tolerance should be considered in the long-term. There are many examples of soil spoiled by persistent application of poor quality irrigation water in Pakistan, India, Spain, Northern Africa and other regions, although they are often poorly documented.

More serious restrictions appear when water is intended for drinking purposes. Salinity should be low, although the commonly acceptable value of 0.5 g/L of total dissolved solids could be increased when no other water is available, especially in semi-arid, arid, and coastal areas. This means that tolerance to Cl and SO_4 and to earth-alkaline ions is admissible, although not as much for Na since an excess over Ca may affect health. Water hardness should be low for cooking purposes and in order to avoid clogging and encrustation of pipes.

Recommendations and norms are strict for nitrate (NO_3) and some minor components with acute or cumulative effects. Tolerance should be minimal for these components. It is not rare that limits are reduced as more medical experience is gained. Such is the recent case of arsenic, whose limit has been lowered from 50 μg/L to 10 μg/L As.

Improved analytical methods allow to detect and measure a much larger number of new compounds – many of which of recent introduction (Table 2) – and help in medical research on human health related to drinking water conditions.

Tolerance to some substances may be argued when drinking water is not the only source of a concerning substance to population. However, since there are alternatives for food but not for water, this explains the strict behaviour of sanitary authorities when referring to water for drinking and cooking.

Table 2. Progress in detection level of possible groundwater contaminants (adapted from Ronen** et al.**, 2012)

Moment	Contaminant	Level of detection
1950s	Major solutes Nitrates Dissolved organic carbon	mg/L (10^{-3} g/L)
1960s	Heavy metals Rare heavy metals Pesticides and herbicides Hydrocarbons	μg/L (10^{-6} g/L)
1980s	VOCs (volatile organic carbons) Chlorinated solvents	ng/L (10^{-9} g/L)
1990s	Hormones and endocrine disruptors Antibiotics Other emergent contaminants	pg/L (10^{-12} g/L)

Similar restrictions to drinking water apply for livestock, although they are more tolerant in what refers to salinity and some components. There is some controversy in what refers to arsenic and other solutes.

For domestic and urban use, and also in modern irrigation systems, hard ground water equilibrated with high CO_2 pressure in the soil ambient is inconvenient, since it produces encrustations when the CO_2 escapes, and may need previous treatment. Dissolved Fe and Mn are also serious problems to all uses, staining surfaces, producing colour, encrustations and blocking pipes, as well as small holes and the tubing of modern irrigation systems. Treatment is affordable for drinking purposes and industrial uses, but this may be a serious burden for population in poor regions, and not affordable for agriculture and livestock, except for special crops and intensive livestock.

3.3 Impact of climate variability on natural groundwater quality

Under natural conditions, aquifers are not static but evolving systems due to past climate variability, land erosion, large land-use changes, sediment accumulation, shoreline changes and other processes. Small aquifers in well-recharged areas adapt rapidly to changes, but large aquifer systems, which have a large water storage, may evolve so slowly – particularly under semi-arid and arid conditions – that they may be considered as being under long-term transient conditions for planning and management purposes, especially in what refers to water quality. Even groundwater quality may not correspond to current recharge. To understand quality patterns, the transient situation has to be considered. Yet, it has to be taken into account that aquifer exploitation accelerates changes because of an enhanced groundwater flow due to greater head gradients. This may be regionally important, especially when referring to vertical water movements. However, existing natural head gradients may be decreased, cancelled and even reversed in some cases.

Climate variability effects may be still preserved in poorly renovating parts of aquifer systems, whose turnover time is similar or longer than climatic cycles. This happens most likely in aquitards and dead-end confined aquifers. At historical and sub-historical time scale, this manifests as relict salinity in recent coastal sediments deposited after the recovery from the glacial age low sea-stand, about 10 000 years ago. Recently recharged water may slowly replace saline water by flushing it out, depending on hydraulic heads, which are controlled by topography, recharge and aquifer properties. While in some cases the flushing process is accomplished, in others it is in its early stages.

In current arid zones, water that was recharged in rainier or favourable-for-recharge past periods may be partly preserved. This old groundwater – often called palaeo-groundwater – is still there due to current, much lower, recharge and/or to the large dimensions of the aquifer (Edmunds and Milne, 2001). This is important in the Mediterranean, Sub–Saharan Africa, north-eastern South America and the Near and Middle East, where relatively fresh palaeo-groundwater is found and used.

Future climate change is very uncertain. The impact on groundwater has been assessed (Medina, 2010) and is quantifiable (Holman *et al.*, 2012) in what refers to recharge and mineral quality, but there is still a wide uncertainty in what refers to other components. The effect on groundwater quality depends on a combination of precipitation and its temporal pattern and the effect of temperature on soil-water balance for the future vegetal cover, taking into account the rate of substitution of current vegetation cover. No dramatic changes in groundwater quality due to climate change are expected during the next decades, except for recharge salinity under extreme situations of dryness or coldness.

A main concern for groundwater quality governance, in most cases, is not climate change but global change, which depends on population, human activity, living standards, land-use and other factors related to development. The impact of these global changes will be dominant, at least in the coming decades, something that is not always duly considered in groundwater planning, research and knowledge transfer.

Forecasts in coastal areas point to a sea level rise of about 0.5 to 2 m. This will significantly impact coastal aquifer freshwater resources only in very flat areas or in low elevation small islands, such as atolls, where the freshwater body may be greatly impacted and reduced. This is a groundwater quality governance issue in some areas in Europe, such as The Netherlands and north-eastern Germany, in part of the eastern coastal areas of North America and in many of the flat small islands in the Pacific. They depend on coastal sediment dynamics, some of which depend also on current activities, such as harbouring, beach modification and erosion changes in streams, as part of global change.

3.4 Governance of groundwater natural quality

Governance of groundwater natural quality refers to management under conditions of poor quality and aims to preserve quality when there are threats from poor natural quality around, above or below the aquifer. Thus, a first step for governance is understanding the origin of the natural quality of the aquifer under consideration and of the other related surface and groundwater bodies. Once there is some aquifer development, then the aquifer is disturbed, and this modifies the flow pattern, locally for small extractions, and affects the whole system for intensive development. The result is induced groundwater displacement inside the aquifer – a slow but sustained process. Besides, wells and other groundwater abstraction works get mixed water from different layers. Their drilling and construction activities may disturb natural flow by introducing by-passes, when low permeability layers are penetrated without carefully grouting the space between the hole and the casing. The same happens when the protection provided by the soil is lessened by breaching it or changing its characteristics, as it is the case in agriculture and deforestation.

When groundwater quality is poor in large areas, management goals intend to minimize the problem (Roset-Palma, 2002) by exploiting the best areas. This means that there is the possibility of institutionalized action over the whole area instead of individual or unrelated and myopic decisions by small groups. However, personal or local action is the most common case, as in Bangladesh with respect the presence of arsenic in groundwater, or salinity in many coastal aquifers. This form of management needs progressive adjustments since the background may change as development progresses. An important improvement that can be introduced, once the causes of poor quality are well understood, is to modify wells (by deepening, shortening, grouting some parts or drilling new well-designed ones), which requires financial resources from the local community or from external sources.

An important issue to bear in mind for groundwater quality governance is that investments to improve currently abstracted groundwater quality, or to ensure its treatment, may be effective for some time but there is a mid- to long-term evolution.

When groundwater quality problems are due to well construction or their inadequate operation, norms are needed. Governance in this case implies getting acceptance of the norms and of the costs involved, as they are paid directly by the groundwater users. It also implies the presence of institutions to set norms and control their application, and as well as to enforce effective sanctions and/or promote compliance among users.

Natural groundwater quality governance has to take into account the different aspects involved and should consider the aquifer system as a whole. A sectoral focus helps to address specific situations and problems, but must be modulated by a global point of view.

4 Human and Induced Changes in Groundwater Quality

4.1 Importance of groundwater behaviour

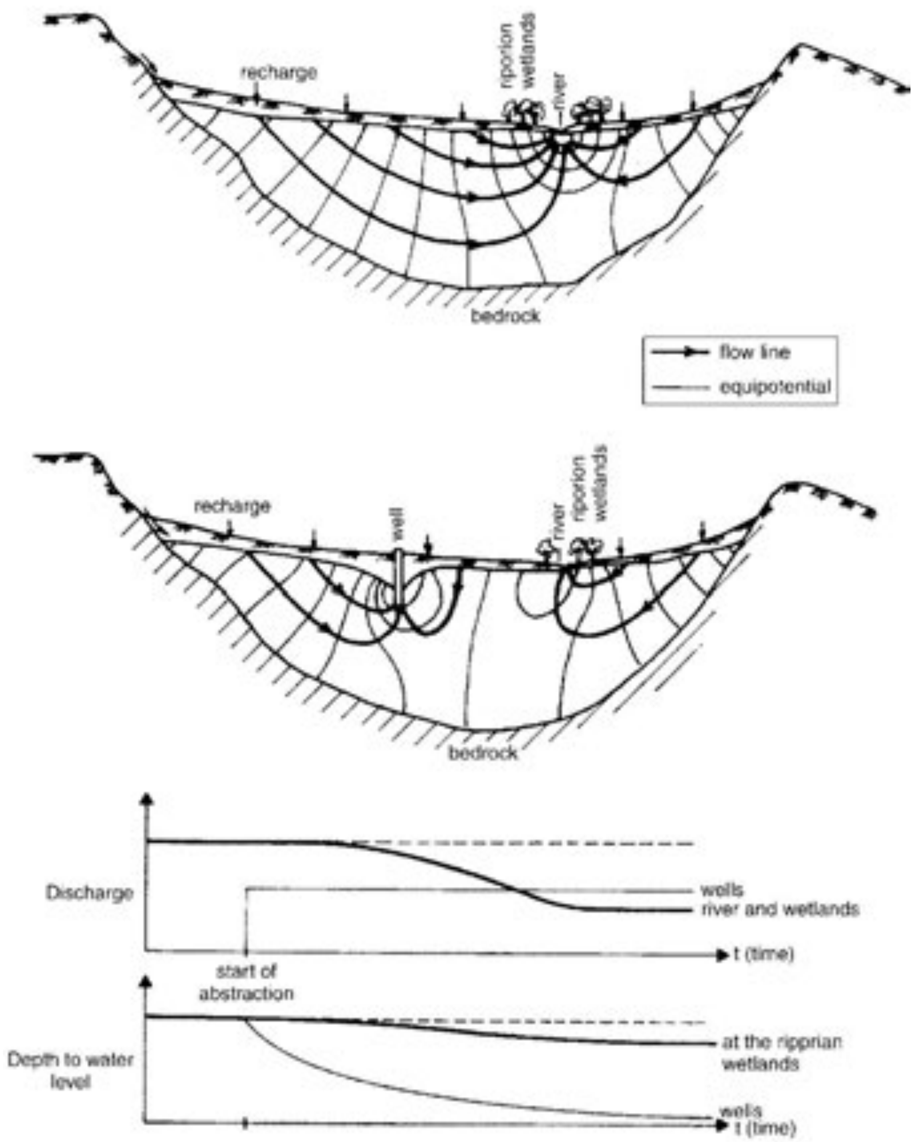


Figure 5. Schematic representation of groundwater withdrawal effects in a sedimentary basin recharged by rainfall infiltration and discharge into a river and through the associated riparian vegetation.

A) Natural situation; B) Long–term effect of intensive groundwater development, in which a generalized water–table drawdown is produced in order to divert a large fraction of recharge to the well area, thus reducing discharge into the river and riparian vegetation area; C) Evolution or river and riparian discharge, and of groundwater level at the wells and at the riparian wetlands; the time scale may vary from months to centuries, depending on aquifer hydraulic characteristics and size. In this case only a fraction of recharge is withdrawn, so a new steady situation will be attained after some time, albeit with some water-table and piezometric draw-down (After Custodio, 2010a).

In managing groundwater resources, governance arrangements have to take into account the sluggishness of groundwater flow and mass transport, which may determine transit times of years or decades, and even centuries or millennia in large aquifer systems (see Figure 5 for the delay of hydraulic changes). Quality changes are often much slower. Thus, the effects of current human activities on groundwater quality may often appear highly delayed, and cause–effect relationships may be difficult to establish. Solutes that can be sorbed or ion-exchanged are still more delayed, attenuated and dispersed. This also means that in some situations current problems are due to activities done decades ago, and that current activities may produce effects that will impact on future generations. This is also true for groundwater quality changes due to land-use activities, such as urbanization, extensive agriculture and changes in forest areas and management. They affect recharge, salinity and quality, besides the possible contribution of contaminants from agricultural practices or the mobilization of those held in the ground.

The medium- and long-term changes – approximately 5 to 10 years and 20 to 30 years respectively – are not easily understood by managers and people in general. Consequently, they are often disregarded when facing pressing short-term problems. Besides, information is often poor and legislation and norms generally do not help. A necessary step for groundwater quality governance is making authorities, institutions and users aware about the slow behaviour of groundwater and about the fact that current problems may come from past activities, thus creating an ethical/moral duty to 'care for the future'.

4.2 Groundwater development effects

Human activities induce two kinds of changes in groundwater quality: introducing contaminants – which cause pollution – and modifying recharge, as well as the flow and mass-transport characteristics of aquifers. As just seen, although impacts were produced earlier in time, they did not become significant until recently – except for large land-use changes and local actions, such as mining activities – when current urban and transportation habits were consolidated and groundwater intensive exploitation started taking place, as shown in Figure 1.

Groundwater development implies decreased water-table and piezometric levels. This not only decreases natural discharges but may also enhance surface water infiltration, inter-aquifer leakage and seawater intrusion in coastal areas.

Surface water infiltration carries the contaminants that have not been filtered out and retained on the surface. The desiccation of wetlands and peat-lands may mobilize solutes and contaminants held in sediments and the organic matter they contain, as some heavy metals.

Inter-aquifer transfer may induce the movement of possible low quality and saline water toward the exploited aquifer, from other aquifers and aquitards or from other areas of the aquifer, such as deep-seated saline groundwater layers containing undesirable solutes due to their special chemical conditions, and the infiltration of groundwater from the sides.

4.3 Pollution effects

Pollution by human activities involves a large series of substances of widely variable origin and diverse contamination processes. Figure 6 shows a cartoon of general polluting activities in a given territory. There are two end-member pollution processes: diffuse and point pollution.

Diffuse pollution – or non-point pollution – refers to a large territory (see Figure 7). Contamination may be air-borne – a main source in many areas, which may involve soluble salts, volatile nitrogen compounds, organic solvents, hydrocarbons and organics – or caused by agriculture and extensive animal raising, which involve agrochemicals, nutrients, water and soil quality correctors, pesticides, herbicides and other similar chemicals. The effect may be quite serious for intensive irrigated crops, but it is also important in dry (rain-fed) farming, which also uses agrochemicals, in lower doses but over larger surface areas. Among the nutrients, nitrate-nitrogen (N) and potassium (K) are quite mobile, while phosphorous (P) is easily retained by carbonate formations.

Figure 6. Cartoon on the main contamination sources and water paths through the soil and a water–table aquifer, in an area with rural, industrial and urban influence (after Lawrence and O'Dochartaigh, 1998).

4.4 Groundwater quality governance of human and induced changes

Groundwater quality governance should deal with groundwater development as one of the key components. Governance arrangements depend on national policies concerning water development, the producers' attitude and the demand. In many circumstances, water demand is driven by quantity, although when water is for drinking purposes there is a growing concern on quality after information to the public improves and the intervention of sanitary authorities becomes more effective. This refers not only to local population but also to the increasing mobility of persons, tourists and food products. Even agriculture – a main groundwater demander in many regions – is becoming concerned about groundwater quality as improved irrigation techniques are introduced, such as sprinklers and drip irrigation, and is looking for efficiency in water, agrochemicals and energy use.

Fighting and managing pollution depend on the understanding of the involved processes and on the interpretation of monitoring data. Groundwater quality governance has to go hand in hand with authorities, institutions and people that decide on land-use, application of agrochemicals, wastes and wastewater policies and activities, and has to rely on public education on these issues.

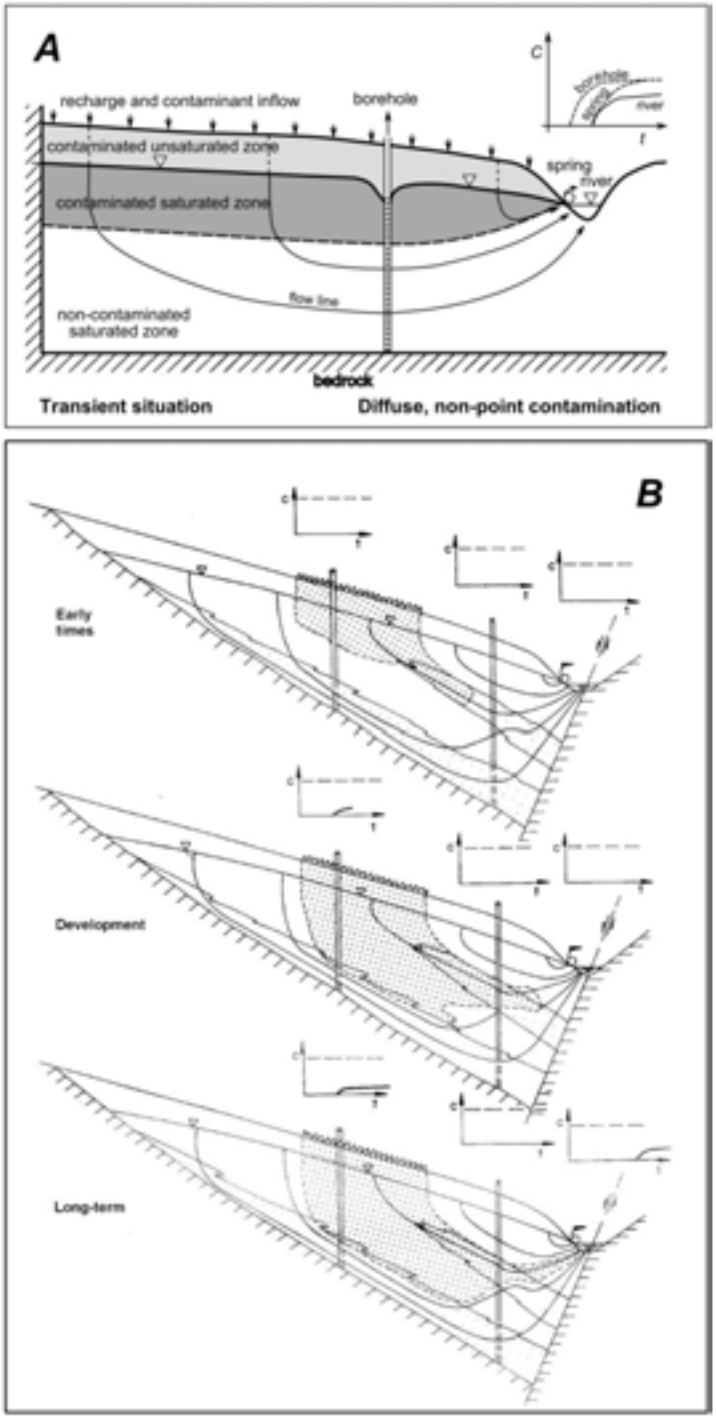


Figure 7. Diffuse (non–point) groundwater contamination from a sustained fertilized agricultural area.
A) on the whole area in a homogeneous aquifer; this is a transient situation since the contaminated area expands progressively if agricultural activity persists; B) over a part of the area of a heterogeneous aquifer. The inserts show how contamination appears in the river, the spring and a borehole. c is concentration and t is time.

Point pollution refers to the introduction of contaminants in relatively small areas by a wide variety of circumstances and activities, such as leakage, disposal of wastes, accidental spills, storage of chemicals and wastewater infiltration and injection. They produce contaminant plumes that move laterally and may sink with groundwater flow (Figure 8). Very important point-pollution activities over large areas – which grade into diffuse pollution – are domestic water disposal in urban and peri–urban areas, irrigation of small land plots and concentrated feedstock. The less economically developed the area is, the more widespread such activities are.

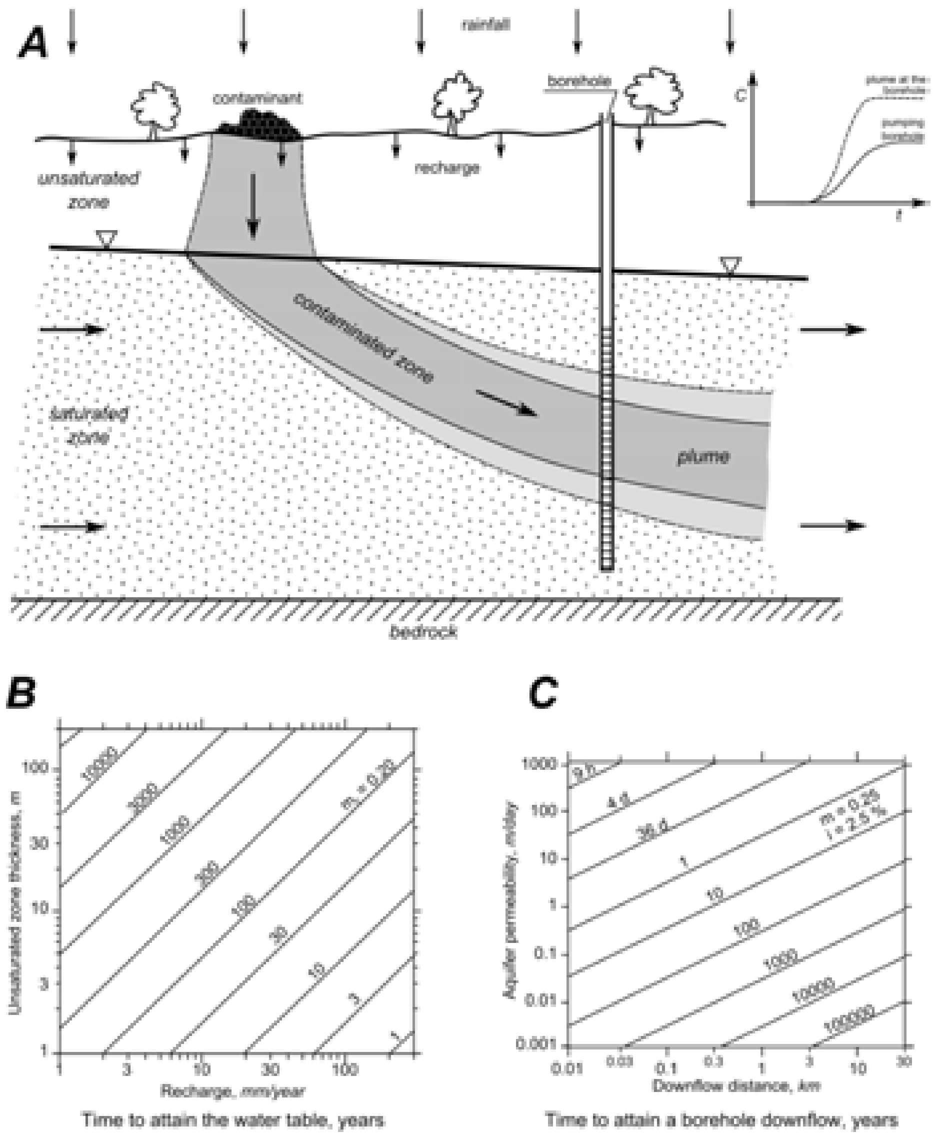


Figure 8. Point (concentrated) groundwater contamination from a disposal site on the land surface, leached by rainfall infiltration that produces recharge through it, in a homogeneous water–table aquifer.

A) contaminated plume; the insert shows the evolution of concentration (c) along time(t) at a borehole downflow and intersecting the plume, in the screen and when pumped; B) time (in years) for the contaminated recharge to attain the water table, considering the unsaturated zone thickness and the recharge rate through the tip, for a 0.2 soil water content; C) time (in years) for the plume to attain a borehole on the plume path, according to aquifer permeability and down–tip distance, for a 0.3 dynamic porosity.

5 Groundwater Quality Conditions and Governance in Selected Typological Environments

Groundwater quality is highly variable, depending on aquifer circumstances and characteristics, and may change inside a given aquifer, both horizontally and vertically. The natural situation – or “normal” situation in highly modified aquifers – has to be known or deduced, in order to determine a reference background value or baseline.

Baseline values are required for the application of the European Water Framework Directive in the EU Member States, following the guidelines of the “daughter” Directive on Groundwater (Directive 2006/118/EC of 12 December 2006 on the protection of groundwater against pollution and deterioration). This has been and still is a controversial issue due to the above-mentioned spatial variability. Several typological environments are presented here as examples, although they do not cover all possible situations.

5.1 Water quality in under-exploited aquifers in under-populated, rural and urban circumstances

Under-exploited aquifers are in principle under close-to-natural hydrodynamic conditions, although not necessarily from the water quality point of view.

Baseline quality conditions are easy to obtain by avoiding wells and springs near urban areas, houses, irrigated cropland and fertilized land. These baseline conditions are highly variable and depend on local, climatic, geological and hydrogeological circumstances, as well as depth. Thus, zoning may be needed to set baseline values and to define sub-aquifers according to depth when guide-layers can be identified.

In rural environments, point pollution sources are mostly related to local sanitation and to the disposal of solids and animal wastes. The impact is usually low, except for high-density rural population, as in many areas of eastern and south-eastern Asia. In some cases, animal impact on water quality may be larger than human pressure. There is a difference between dispersed houses and the concentration in small and medium villages. Villages may severely affect a given territory, which is proportionally small but important for inhabitants who usually rely on close-by groundwater resources that may be close to sanitary disposal sites or poorly isolated from land surface. This is often a major source of health problems, including from the use of household chemicals, such as detergents and oily products. Groundwater quality governance arrangements should bear in mind that, although some dangerous chemicals –often cheap ones– are banned and not used in areas where legal restrictions are enforced, they may continue to be produced and used in poor areas, thus easily getting into the neighbouring shallow aquifers.

Pathogenic problems are only found in groundwater in the case of shallow water table, where there is a poor soil cover or where the soil cover has been disrupted and breached by excavation or drilling. However, coarse materials allow the spreading of bacteria and viruses to the surroundings before they decay. To limit the access of surface contaminants to the water table, the preservation of soil cover is very important. However, even when groundwater is not polluted, contamination of abstracted water may result from poor well construction, isolation and protection of the immediate surroundings. This is often the cause of many health-related problems attributed to groundwater. Thus, appropriate well construction and operation is important to avoid contamination; this may include careful grouting, isolation and protection against corrosion and tubing ruptures. Well construction is often done following the cheaper bid, without clear prescriptions and control that guarantee water quality aspects. This is a source of problems and also kills existing good practices. Adequate well construction may be difficult in poor areas.

Under rural environments, agriculture and feedstock may be – and often are – an important source of aquifer contamination and produce progressive nitrate content increases that may spoil aquifer use. Governance of groundwater quality implies involving institutions and people in sanitation, adequate use of household chemicals, good agricultural and livestock practices, safe storage of potentially polluting substances and safe disposal of refuse. In addition, it is necessary to promote, regulate and provide means for the adequate construction, operation and maintenance of wells, while keeping their surroundings clean. The rural and small village environment needs direct involvement of people, for their own sake and to preserve their common-pool resource (Burness and Brill, 2011).

Groundwater quality is generally impaired under urban environments, even if actual recharge is often still important (Chilton, 1997, 1999; Custodio, 1997; Foster *et al.*, 2011), contrary to what is generally assumed. Figure 9 shows a cartoon on pollution sources. Common contamination problems refer to nitrate increase (see Figure 10), mineral oils, fuels, chlorinated solvents leakage and occasionally the creation of a reducing environment when organic matter concentration is high, which may produce the dissolution of Fe and Mn or the release of trapped As. Separate phase pollutant liquids or non-miscible phase liquids (NPL), which are partly soluble in water in small to medium concentrations, may be lighter then water (LNPL) and float around the water table (Figure 11) or denser (DNPL), in which case they sink through the saturated zone (Figure 12). Besides, a large series of chemicals at low concentration may be found, which are generically called emergent contaminants (Drewes *et al.*, 2003; Shey *et al.*, 2006). They include caffeine, nicotine, pharmaceuticals, antibiotics, estrogens, endocrine substances, cosmetics and psychedelic drugs, whose effect on human health is poorly known. They may be found even in poor urban sectors or near infiltrating polluted rivers. Groundwater may reflect local supply water quality (Vázquez–Suñé *et al.*, 1999). This is an important but poorly understood evolving issue that might have serious impacts on human consumption, as well as on the environment and its services.

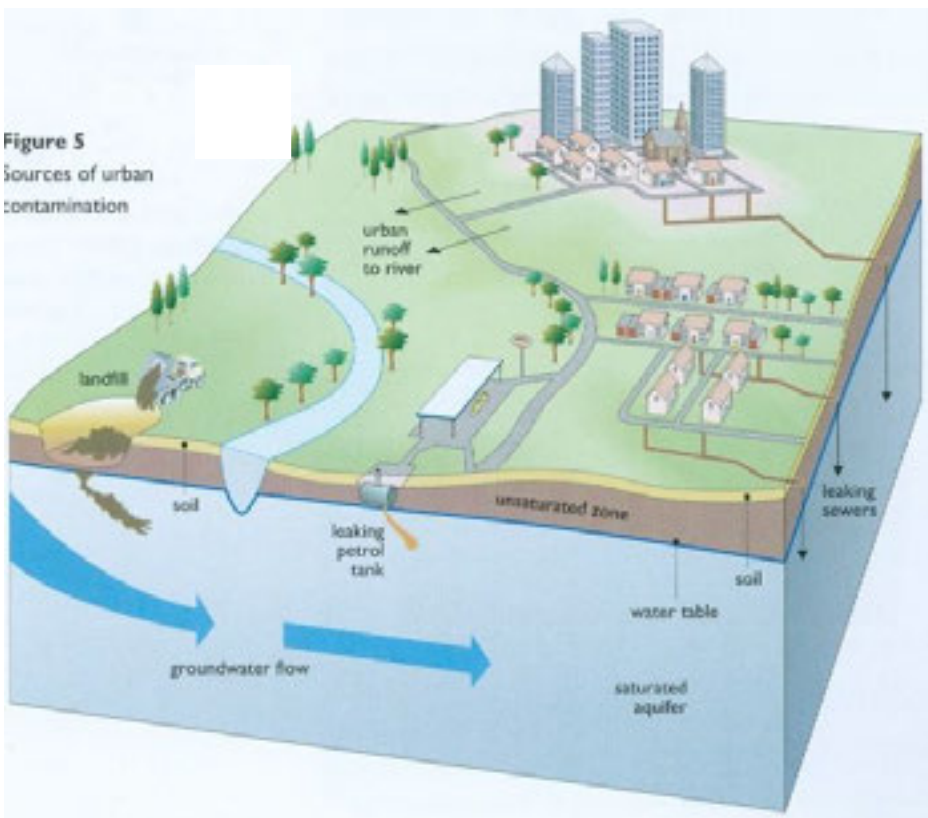


Figure 9. Cartoon showing the main sources of contamination in an urban and peri–urban area (Lawrence and O'Dochartaigh, 1998).

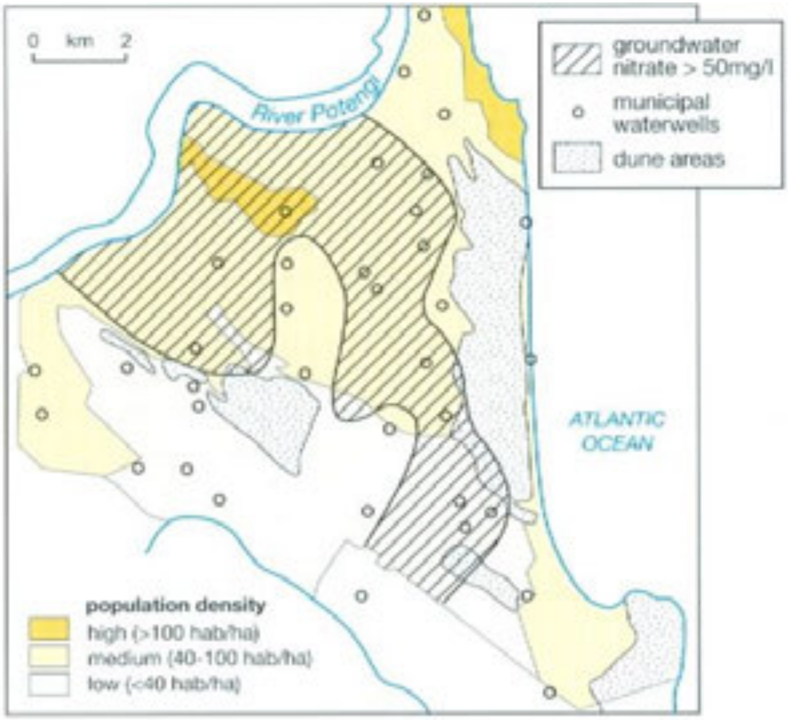


Figure 10. Example of nitrate contamination of mixed urban and agricultural origin in the city of Natal, Brazil, in 2008 (Foster et al., 2011).

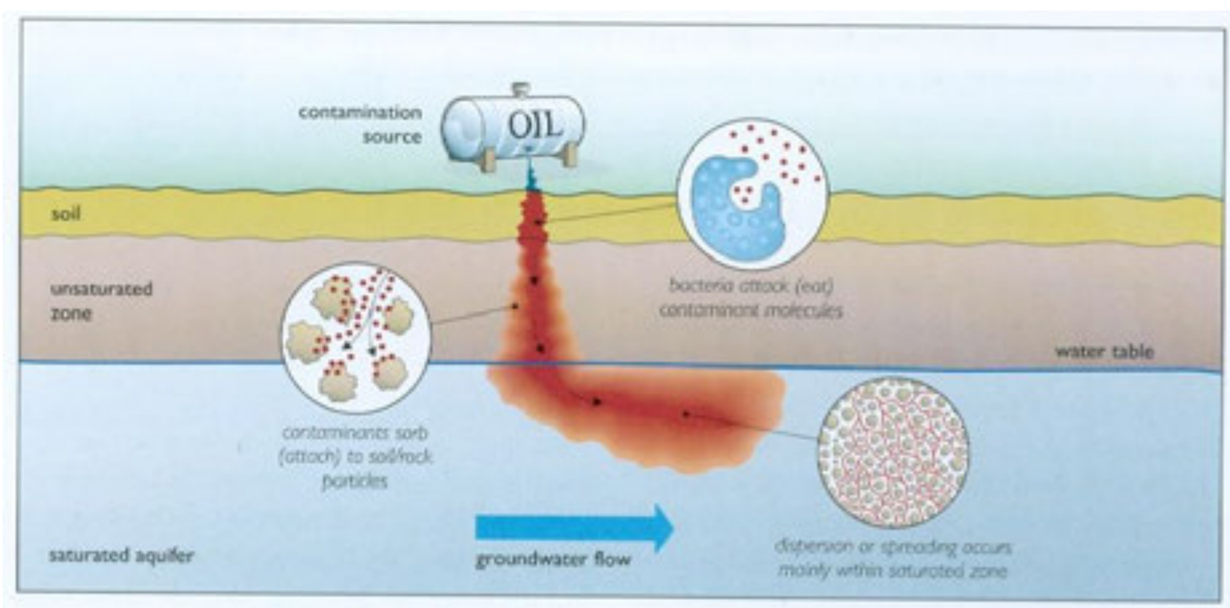


Figure 11. Soil and aquifer pollution by oil tank spills and leakages.

Mineral oil is a lighter than water, non–miscible phase liquid (LNPL) that floats on the water table; it is slightly soluble in water and disperses according to water–table fluctuations and groundwater flow (Lawrence and O'Dochertaigh, 1998). Under favourable circumstances, natural processes may help in reducing contamination through degradation, sorption and dispersion.

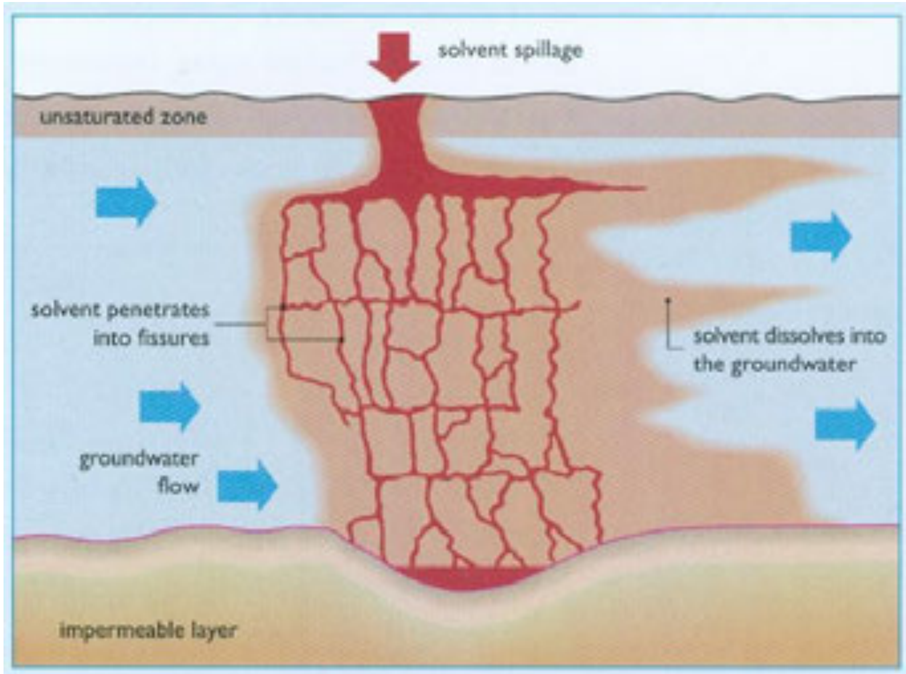


Figure 12. Soil and fractured aquifer pollution by chlorinated solvents spillage.
They are denser than water, non–miscible phase liquids (DNPL) that sink slowly through the whole unsaturated zone thickness and cumulate in the aquifer bottom; the plume and main body contaminates groundwater in contact with them due to the slight solubility (Lawrence and O'Dochertaigh, 1998).

Groundwater quality governance is a difficult issue due to the multiple and densely distributed sources of pollution, in a human environment that is not aware or does not value groundwater. Awareness raising activities are needed to promote the progressive reduction and elimination of pollution sources. The government, with the help of civil institutions, has to regulate urban activities, such as storage of fuels and chemicals or collection and disposal of wastes, and replace individual sanitation systems with common and well-maintained sewage systems. This is an achievable goal in relatively rich areas, but a serious challenge in poor cities and marginal areas of otherwise rich towns, such as Buenos Aires, Lima, Mexico City and São Paulo metropolitan areas, as well as many large cities in India. Local groundwater resources from urban areas can be used for non-potable uses – street cleaning, building, industrial cooling and other industrial uses – or for drinking purposes if thorough and safe treatment can be provided. Related expenses will have to be borne by residents or subsidized, when appropriate. In some cases, groundwater exploitation has to be encouraged to avoid problems with high water tables or to delay costly importation of water.

5.2 Water quality in intensively exploited aquifers in arid regions

In an intensively exploited aquifer, abstraction is a significant fraction of recharge. Consequently natural flow conditions and water quality are notably modified. The use of the term overexploitation may be misleading (Custodio, 2002), since it often conveys a negative point of view, which is not necessarily true, or suggest that exploitation is greater than recharge, which may not be the actual case. At least for some time, groundwater exploitation and groundwater mining – the continuous depletion of aquifer reserves – may evolve similarly. Moreover, exploitation and recharge rates are rather difficult to determine and are often highly uncertain. From the point of view of groundwater quality, the abstraction of a fraction of recharge may lead to a clearly unsustainable situation, as in coastal aquifers or when saline groundwater is found below. Contrarily, an exploitation rate greater than recharge can be advisable, without causing serious water quality problems, if freshwater reserves are large and the supplied society is evolving towards new conditions where groundwater mining will not be needed (Foster and Loucks, 2006; Custodio, 2010a).

Determining the baseline quality is not an easy task, since surveys and monitoring are often carried out when aquifer disturbance is already advanced. Careful studies and occasionally drilling surveys are needed. In some cases, the baseline has to be referred to conditions in which aquifer water is from recent recharge under prevailing disturbed conditions.

In intensively exploited aquifers, some degree of water quality impairment may be produced, but this is not the general rule. Aquifer conditions define the evolution. Major threats are saline degradation from seawater intrusion or from existing saline water in aquitards and deep formations, and occasionally the release of natural contaminants from the formerly saturated zone that has become unsaturated and exposed to atmospheric oxygen. Such are hardness increase and pH lowering when organic matter is degraded, which may be accompanied by the release of some heavy metals, among which arsenic. Groundwater use for irrigation may cause salinity problems, besides those derived from fertilizers, especially nitrate build-up. Salinity increase may be due to highly saline irrigation return flows – the more efficient the water use, the more saline the return flow – and to leaching of salts in formerly saline soils and overlaying formations. Saline contamination is found below the irrigated areas and spreads downflow slowly since, in most cases, head gradients are small. This may severely affect water-table aquifers and, consequently, deeper aquifers of local relevance when wells are not well isolated. In deep water-tables, contamination may only appear after years or decades and may even go unnoticed for a longer time if there are no wells to monitor the upper part of the water-table aquifers.

Groundwater quality governance issues, in areas where intensive development is the consequence of water scarcity or concentrated water demand, are often of secondary importance since quantity is prioritized, except when water is dominantly for human supply. But when quality problems eventually appear, things are very difficult to redress due to the long time needed for restoration and the high costs involved. Governance means that coming problems have to be forecasted, and that government and civil society institutions must be aware of the need to preserve the common-pool water resource and of the risks of no action.

A different situation of aquifer salinity deterioration in arid areas is due to the existence of brackish to saline water held in the often thick unsaturated zones. This water is the result of intensive evapo-concentration (water salinity increase due to evaporation and transpiration) of atmospheric salt deposition by highly efficient rainfall use by native vegetation. When the forest is thinned or substituted by prairies and cropland, recharge increases conspicuously due to the lower efficiency of rainfall-water capture. This recharge has a lower salinity but pushes down previous saline water through the unsaturated zone at a higher rate. This generates an increased rate of introduction of salts into the aquifer over time, which may often last decades or centuries. When the main recharge of the aquifer is produced in other more favourable areas, which are less saline, this process leads to salinity deterioration in the aquifers below, affecting local wells and downstream springs and river base-flow (Scanlon *et al.*, 2009) (see Figure 13). This is a serious concern not only in the well-known case of the Murray–Darling basin, in south-eastern Australia (Simpson and Herczerg, 1991), but also in other areas where the problem is not recognized due to lack of monitoring or for being the result of old activities. This seems to be the case of the Monegros area, in north-eastern Spain, a semi-arid area covered by medium-size brush that was cut down for timber and fuel between two to four centuries ago. Taking such issues into account in governance arrangements may prove challenging, as land use and other sectoral activities are involved.

When irrigation with imported water produces a significant recharge increase through more or less saline return flows in otherwise low-recharge areas, the water table may come close to the land surface and become further salinized by direct evaporation from the soil, with detrimental results for agricultural activity and local supplies. An old, well known case is that of the Punjab, in the Indus Plain, Pakistan (Figure 14).

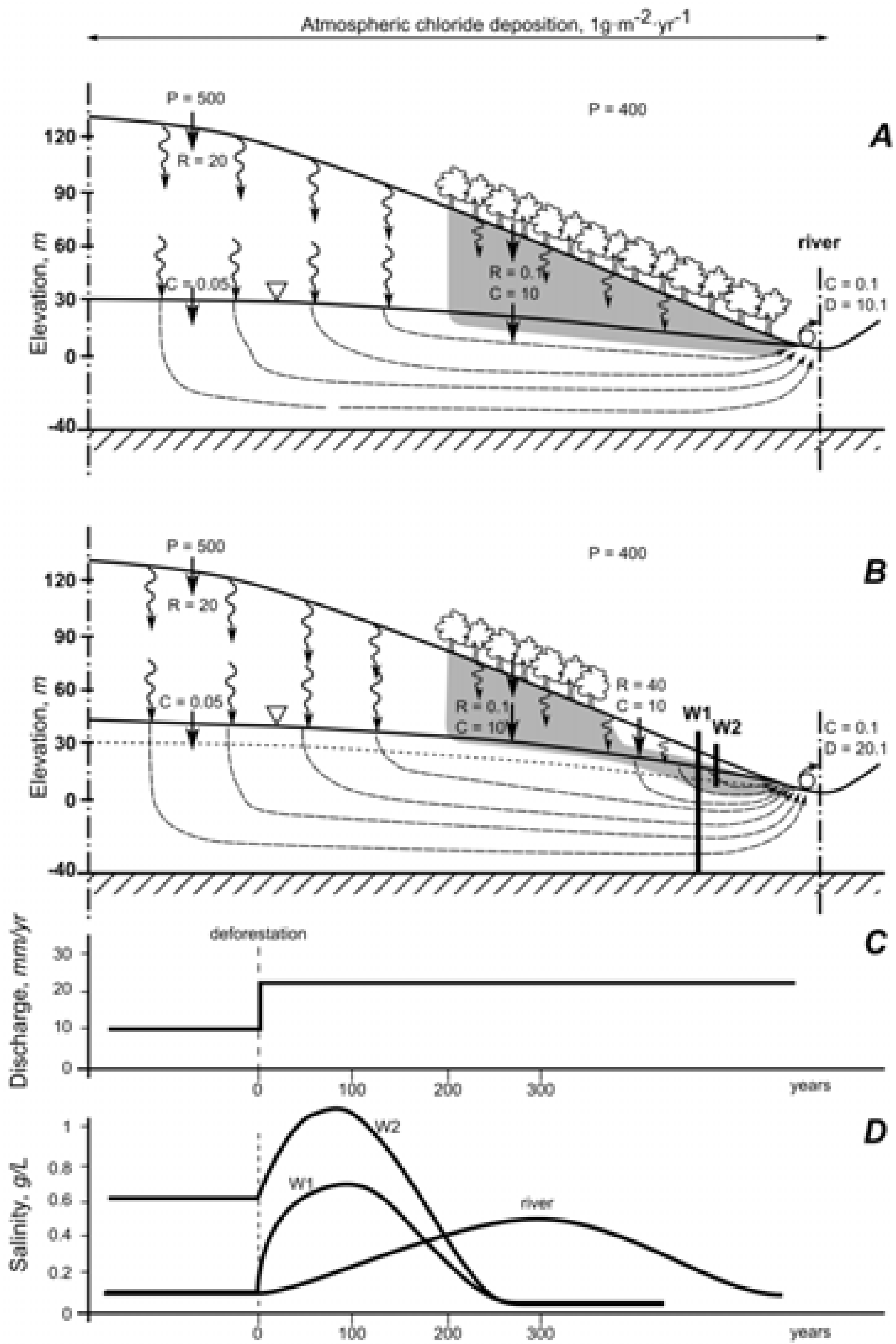


Figure 13. Simplified representation of the leaching down of the saline water hold in the unsaturated zone below a highly efficient natural forest in an arid area, when the aquifer receives freshwater recharge from upflow areas.

A) natural situation; B) transient situation after partial deforestation of the area, C) change in river discharge after increased recharge in the deforested area, D) indicative evolution of salinity in two pumped wells downstream and in the river; the time scale is only indicative and depends on the size of the system. P = average rainfall (mm/yr), R = recharge (mm/yr), D = discharge (mm/yr), C = chloride concentration (g/L). (Modified from Custodio et al., 1997).

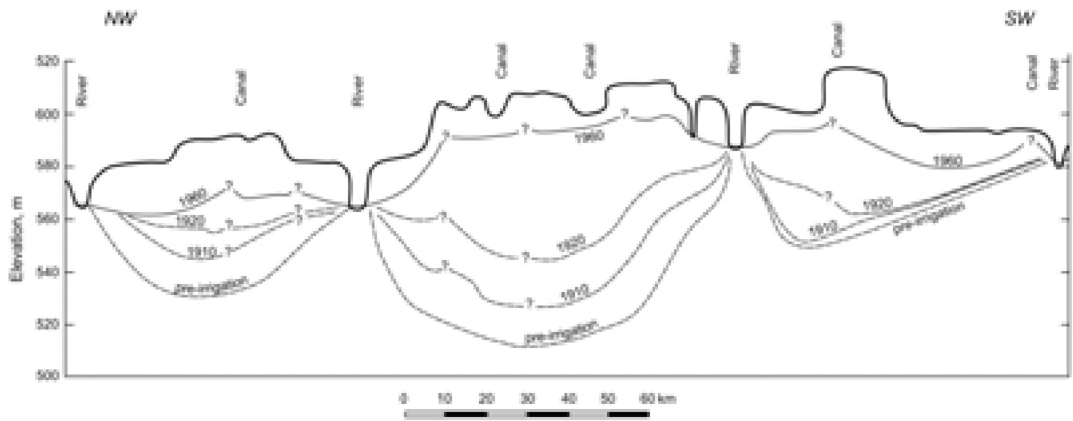


Figure 14. Water–table rise below a plain irrigated with imported water, with added recharge from high canal losses and return irrigation flows, as exemplified from the arid Indus Plain, Punjab, Pakistan (after Greenman et al., 1967). Groundwater evaporation from areas developing very shallow water tables increases salinity and further deteriorates groundwater quality.

5.3 Water quantity evolution in regions of high annual recharge

The main characteristic of regions with high annual recharge is the fast renovation of water in shallow aquifers. Thus, salinity increase due to evapo-concentration and mineral weathering is small, and groundwater mineral quality is close to average rainfall. However, organic-rich soils yield soluble and colloidal organic compounds, mostly humic and fulvic acids, which may become a problem for human supply – although this is not the common case for groundwater, where the Total Organic Carbon (TOC) is at most a few mg/L. In the aquifer, available dissolved oxygen is often consumed, and thus reducing conditions appear. This may be accompanied by Fe and sometimes Mn dissolution, if they are available in minerals, mineral particles or grain coatings. Also nitrate may be reduced to NH_4 instead of N_2, which interferes with water disinfection. Natural vegetation is generally very efficient in capturing available mineral N, except when forest is thinned out or substituted by grassland and agricultural fields, in which case soil organic matter decays and frees the nutrients held in it.

Under these circumstances, baseline quality can be derived through simple sampling, although special local situations may be found, which may need a separate consideration and could be considered as an exception.

In regions of high annual recharge, groundwater quality does not pose serious problems, beyond those mentioned above, due to the fast turnover time of groundwater and the scarce use of groundwater for irrigation, thus easing the pressure on the aquifer. The main issue is related to changes in the underground ambient by local exploitation – some limitation may be needed – and to the control of pollution sources. A frequent pollution source is the use of herbicides to control weeds in open areas, train tracks and roads. When soil is thin, coarse, breached or non-existent, these herbicides may find their way down to the aquifer, where retention may be low thus allowing them to travel some distance along the groundwater flow before they decay – if they do at all. Atrazine and simazine have been - and in many places they are still - commonly used products. Currently, glyphosate formulations are widely used in some cases; they decay fast and do not seem to pose a problem for groundwater, although they may leach downwards to the aquifer from coarse soils on weathered granite and volcanic formations (Candela *et al.*, 2010).

Deep confined aquifers with long turnover time contain freshwater in the outcropping and renovating parts in high recharge areas, but may hold old brackish and saline water in the rest. This is the case in parts of the Guaraní aquifer (ALHSUD, 2007; Heredia *et al.*, 2012), and seems to be the case of the Tikuna confined aquifer in the Upper Amazonas deep aquifer (do Rosario, 2011), both being large trans-boundary aquifers in South-America.

5.4 Groundwater quality evolution related to agricultural development

Most new agricultural areas are established in old forest and brush areas, causing the degradation of organic-rich soil. After available nutrients are depleted, agricultural productivity decreases if not compensated by the application of agrochemicals. In both cases, nutrients are leached down – especially nitrate – that, after some time, appear in the water-table. This depends on recharge and depth of the water table, as well as on the characteristics of the soil and of the unsaturated zone (Foster and Candela, 2008; Candela and Aureli, 1998; Vrba, 1991; Ripa *et al.*, 2006; Landon *et al.*, 2011). Different aspects are considered in Section 5.2.

This is an increasing and expanding problem in most agricultural areas of the world that will continue to grow in developing areas, as greater fertilizer quantities are needed and made available to sustain fertility, especially in intensively cultivated areas. Poor application technology is part of the problem, but even with good technology some leaching is unavoidable, especially in irrigated areas. Existing data show that salinity tends to increase below crop land (Knapp and Baerenklau, 2006).

High concentrations of nitrate – well above the 45 to 50 mg/L limit for drinking water – can be found in many agricultural areas, especially when intensively cultivated and irrigated or due to intensive feedstock farms. Reported values may be up to several hundred mg/L.

Leaching down to the water table of part of the applied nitrate is almost unavoidable (Albiac, 2009), although efforts and modelling helps in reducing the problem (de Paz *et al.*, 2009; Delgado, 2002; Corwin *et al.*, 1997; Jabro *et al.*, 2006). The most common practice is applying an excess of nitrate (Ramos, 2002; Dennehy *et al.*, 2002), above the commonly recommended quantities (150 to 180 t/ha/year). In some cases, the excess is due to other causes that are unrelated to fertilization, which are rarely taken into account. This is the case when applied groundwater has already high nitrate contents and is used as a main source for irrigation water or when this water applied for emergency irrigation to fight possible frost. Such cases are difficult to manage because fertilization and irrigation needs do not occur at the same time (Wallis, 2011; Candela *et al.*, 2008).

The US Environmental Protection Agency (EPA) and the European Commission are seriously dealing with the nitrate problem, as a major water supply problem that requires appropriate management and governance (see Box 4).

Box 4: European Water Directives dealing with groundwater quality

The EU enacted the Nitrates Directive (Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources) to deal with groundwater pollution due to agricultural sources, which includes fertilization, livestock and animal waste storage and use. The Nitrates Directive, jointly with the other Water Directives, has been incorporated into member states legislation and have to be enforced in the respective territories. Vulnerable zones to nitrate pollution of agricultural origin have been defined and are subject to special measures, including limitations to fertilizer use, minimum storage volumes for feedstock wastes and their control, good agricultural practices and an adequate level of monitoring and reporting.

The Water Framework and Groundwater Directives require that by 2015 groundwater bodies identified as legal administrative units – reach good quantity and chemical quality status. This good quality status is close to baseline value of the aquifers. However, due to their characteristics and to the high economic cost of halting and reversing quality trends, a great number of aquifers – about 20 to 50 percent of the groundwater bodies, depending on the country – will not meet the target. If required, new deadlines can be set for the next six-year planning period in 2021, or even for 2027, but this needs careful studies and an action plan with defined and approved steps. The consideration of practically unrecoverable situations is a pending issue that involves problems of comparative grievance and costs transferred to the future. In fact, it is unclear how efficient this action will be, especially considering the cost to society relative to the benefits from improved environmental quality, which is the main objective of the Water Framework Directive. Results for groundwater are currently poor, but it is too early to appreciate future results (Silgram *et al.*, 2005). In spite of stationarity and even further deterioration in some areas, in others improvements are reported, as in The Netherlands (Cramer *et al.*, 2010; Zwart *et al.*, 2008; see Figure B4-1).

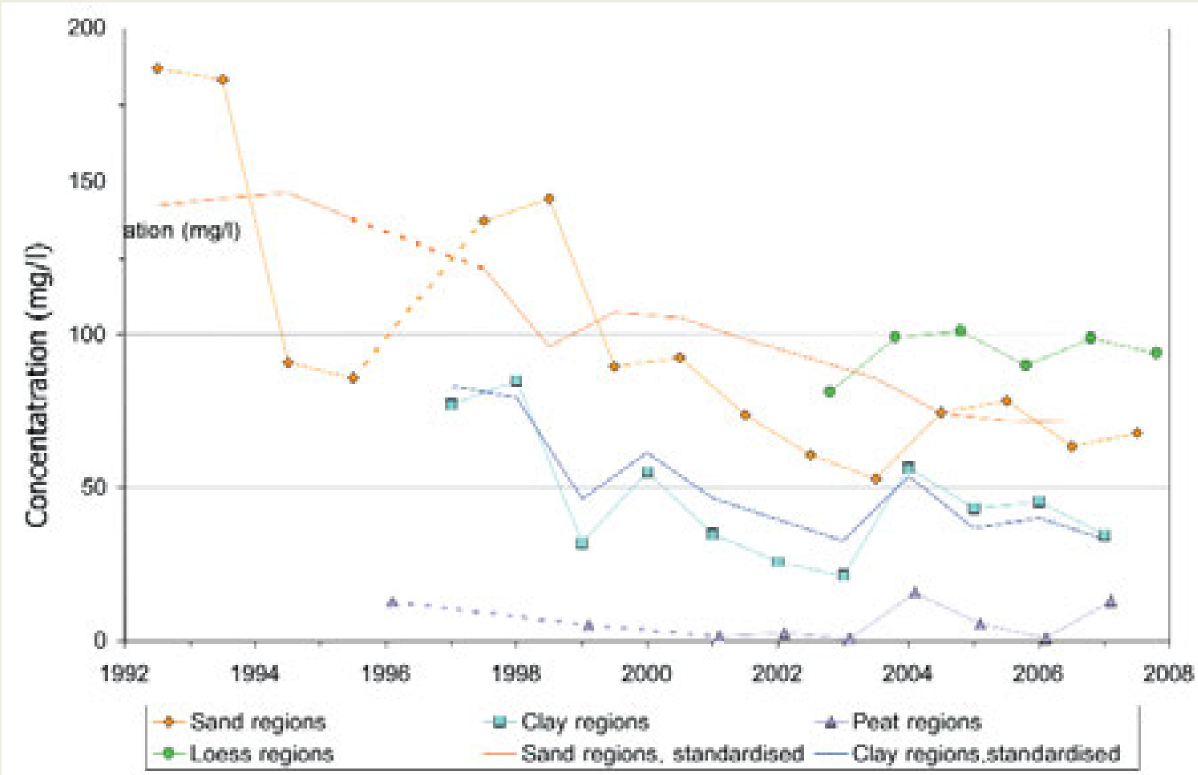


Figure B4-1. Nitrate content improvement in the upper part of the saturated zone in agricultural areas in The Netherlands (after Zwart et al., 2008). Points show annual average nitrate concentration.

How this can be applied to other countries and regions as a groundwater quality governance action related to nitrate pollution is not known. The implementation of such measures is proving complex and expensive even in the EU, particularly in the current difficult economic conjuncture. One option is to consider some aquifers as non usable for drinking purposes, but this transfers a higher cost on drinking-water supply systems and does not prevent that pollution will eventually appear in springs, rivers and the littoral sea, thus frustrating pollution abatement efforts. A number of studies show that in many aquifers, the economically and socially costly action to reduce nitrate pollution will not produce the wanted results for some decades and may result in further deterioration for some time, due to the larger quantity stored in the soil and in the ground. This makes groundwater quality governance a challenging task, as results may be highly delayed.

The use of pesticides in agriculture – a wide variety of them for very different purposes – is a growing concern, as is the use of pharmaceuticals for livestock. Pesticides may be sorbed in the soil, subject to degradation and may produce concerning derivatives (metabolites). There are numerous studies on their behaviour in the soil and in the ground, but effective solutions have yet to be developed (Mouvet, 2008). Baran *et al.* (2010) provide an example from France. Pesticide contamination of groundwater is not only a threat to health, but also an economic loss when supply wells have to be closed down (Figure 15). Governance arrangements should consider that several sectorial government departments are involved in pesticides management and use and have to be coordinated. This is a complex and difficult task that may fail, even in simple situations.

Groundwater salinity pollution by changing natural vegetation for prairies and cultivated areas is considered in Section 5.2.

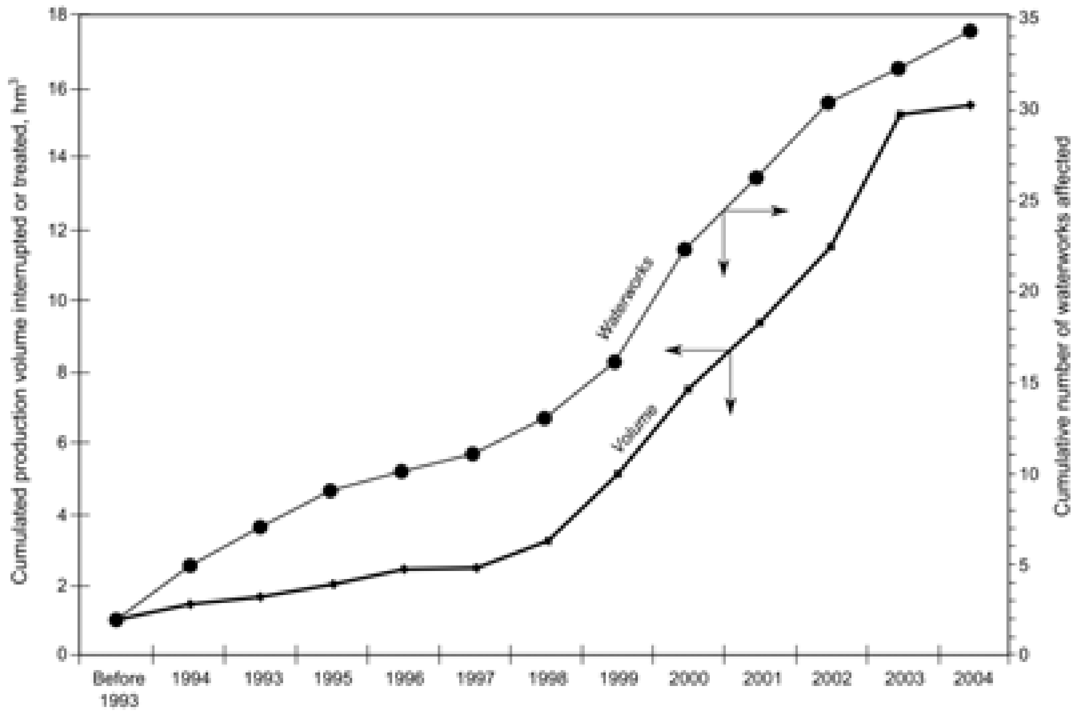


Figure 15. Time evolution of the cumulative volume of groundwater and the number of drinking water production wells closed down or needing water treatment due to pesticide contamination, in Wallony, Belgium (after Mouvet, 2008).

5.5 Saline water in coastal areas

Seawater intrusion in coastal aquifers is the result of hydrodynamic conditions in a variable water-density flow system. Seawater is denser than freshwater and thus tends to penetrate the land from the coast and to lie at the bottom of aquifers. The penetration is limited by groundwater flow, as aquifer properties and geometry define the extent of seawater intrusion (see Figure 16 for a typical example in a recent deltaic area with a dune belt). Groundwater development decreases freshwater flow towards the coast and may even reverse it, which consequently induces seawater inflow. These are well known processes (UNESCO–IHP, 1986; Custodio, 2005). A mixing or transition zone develops between freshwater and salt water, whose thickness depends on local conditions and grows with increasing groundwater development. Abundant information can be found in the proceedings of the 22 Salt Water Intrusion Meetings (SWIM), and in a recent issue of the Hydrogeology Journal (2010). Although the basics are simple, the behaviour of real aquifers is complex due to the large influence of local heterogeneities, groundwater level fluctuations and recent sea-level changes. Seawater advancement is spatially variable and may follow preferential paths through more permeable layers when artificially-induced head gradients are large. This is enhanced in karstic aquifers due to the conspicuous local permeability increase by carbonate rock dissolution.

Many seawater contamination problems are not the direct result of lateral seawater advancement, but are due to water up-coning below wells, drains and excavations, when there is saline water below. This saline water may be of natural origin or the result of the marine water wedge advancement. This creates very complex situations. Even the origin of abstracted water salinity is often unclear, due to mixing with seawater remnants in low permeability parts of recent coastal formations. The infiltration of return irrigation flows may produce similar results. Figure 17 shows an example. In order to screen out the different possible origins, detailed studies are needed. Knowing the right salinity origin and dynamics is important for coastal aquifer governance.

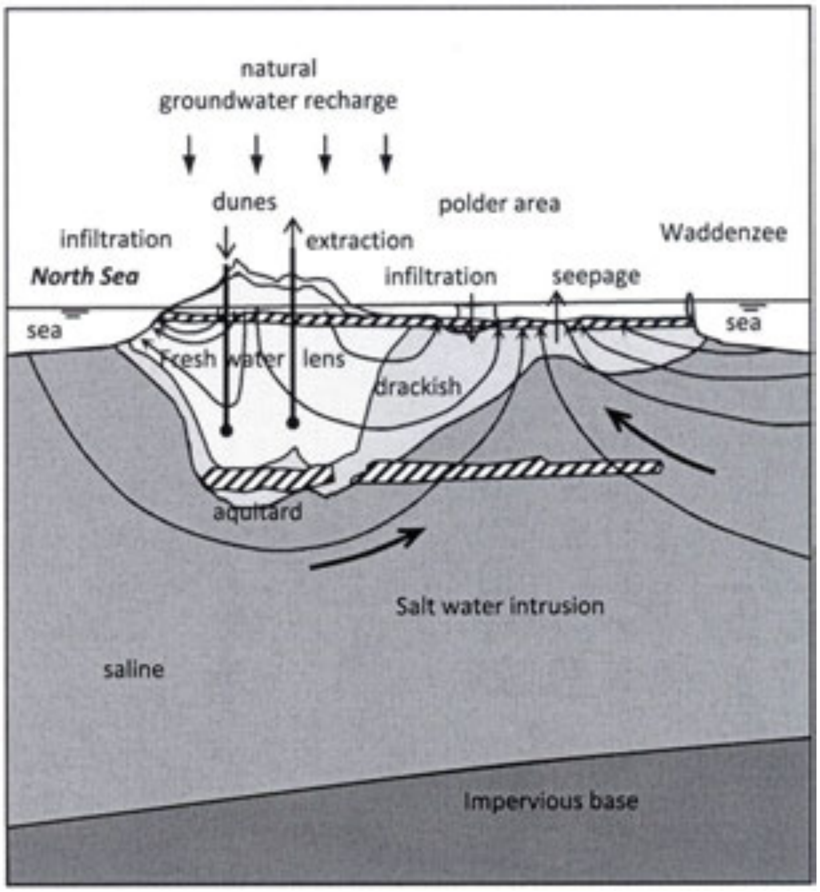


Figure 16. Groundwater salinity in the Rhine delta, near Amsterdam, the Netherlands, due to seawater intrusion in a low–laying, flat area, and the mixing with recharged freshwater in the dune belt and with irrigation water in the polder area.

Seawater intrusion problems are naturally found in many aquifers worldwide (Hydrogeology Journal, 2006; Custodio, 2005; Bocanegra et al., 1992; Cardoso da Silva, 2010), but they are mostly due to groundwater development, with well known cases, such as those of California, Yucatan, eastern USA, The Netherlands, Belgium and northern Germany. Salinity problems in some high-yielding recent coastal formations are important since they supply urban areas without other freshwater sources, as in Mar del Plata, Argentina (Bocanegra *et al.*, 1992) (see Figure 18), or currently as a water source and an important reserve in dry periods, as in the Lower Llobregat area, Barcelona, Spain (Iribar and Custodio, 1992; Custodio, 2012) (see Figure 19).

In coastal aquifer governance, water quality often becomes a dominant concern. Progress has been made in some areas, such as California, The Netherlands and the surroundings of Barcelona. Participation of the involved social sectors and the users is needed, as well as the adoption of rules for safe drilling and well abandonment and of appropriate management techniques, such as abstraction control, redistribution of wells, artificial recharge and hydraulic barriers to limit the seawater wedge penetration. All this has a rather high investment and operation cost.

Deep-seated saline water – often old seawater – is found in many areas of the world, both inland and near the coast. This is a common situation in large areas of northern Germany and Poland, where such water may contaminate wells in these generally well-recharged areas, when wells are too deep, breach clay layers or are excessively pumped. Groundwater quality governance has to take into account the pervasive existence of saline water held in some layers or at depth, and may need limiting well depth, pumping rate and well distribution.

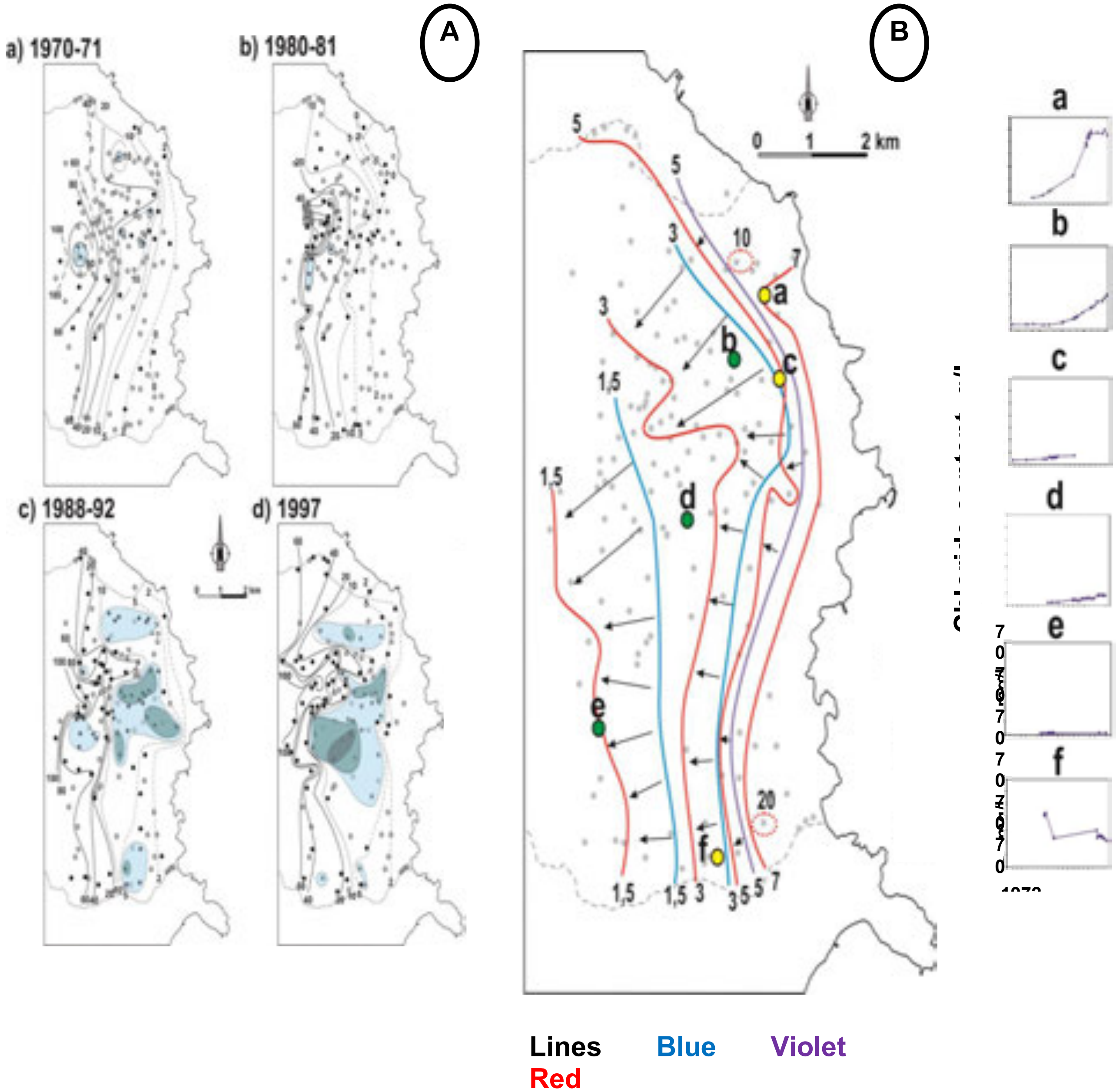


Figure 17. Complex salinization problems in the volcanic and volcaniclastic aquifer of Telde, Gran Canaria, Canary Islands, Spain (after Cabrera and Custodio, 2012).

A) the successive figures show the changes of water–table elevation (in metres) due to intensive aquifer development since 1970, when development was already intensive; shaded areas show water–table levels below sea level, 0 m to –10 m; –10 m to –50 m and deeper than –50 m, according to more intensive gray colour; black points show wells currently used to get brackish water for reverse osmosis desalination. B) progress of chloride content; the insets show chloride content evolution in some wells. Salinization near the coast is due to sea water intrusion and up coning, but in the mid inner area it is due to a combination of return irrigation flow and the use of saline water in industrial and urban activities (Cabrera and Custodio, 2012).

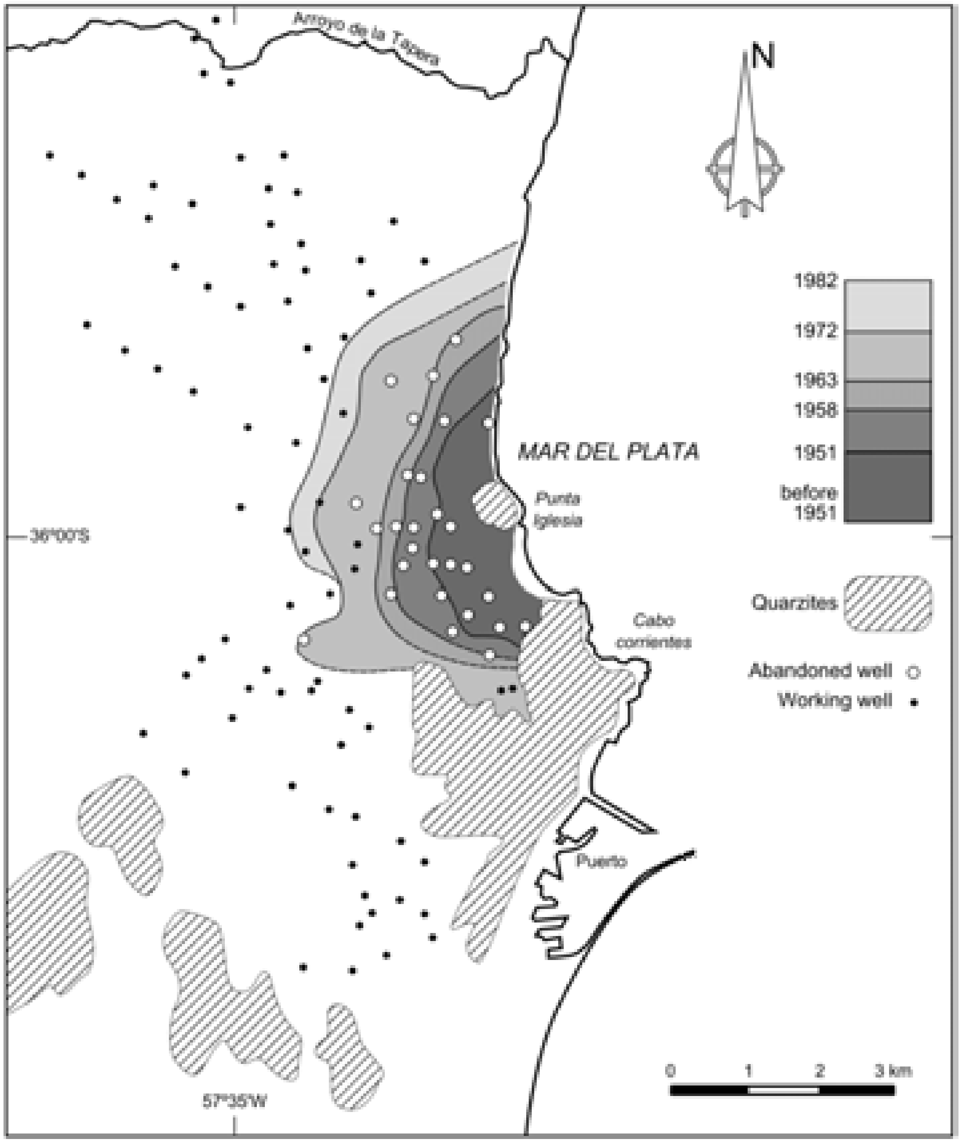


Figure 18. Salinity advancement in the Mar del Plata urban area, Argentina, due to local intensive pumping for supply (after Bocanegra et al., 1992).

Due to salinization problems, wells have been progressively moved away from the town, interfering with rural areas. Governance has meant agreements, in this case not a difficult task since there is only a main groundwater user in the urban area. High salinity wells were closed–down in the town area. This was followed by water-table recovery, in this case brackish to saline water, and further to underground space inundation problems; enhanced corrosion is a concern (Bocanegra et al., 1992).

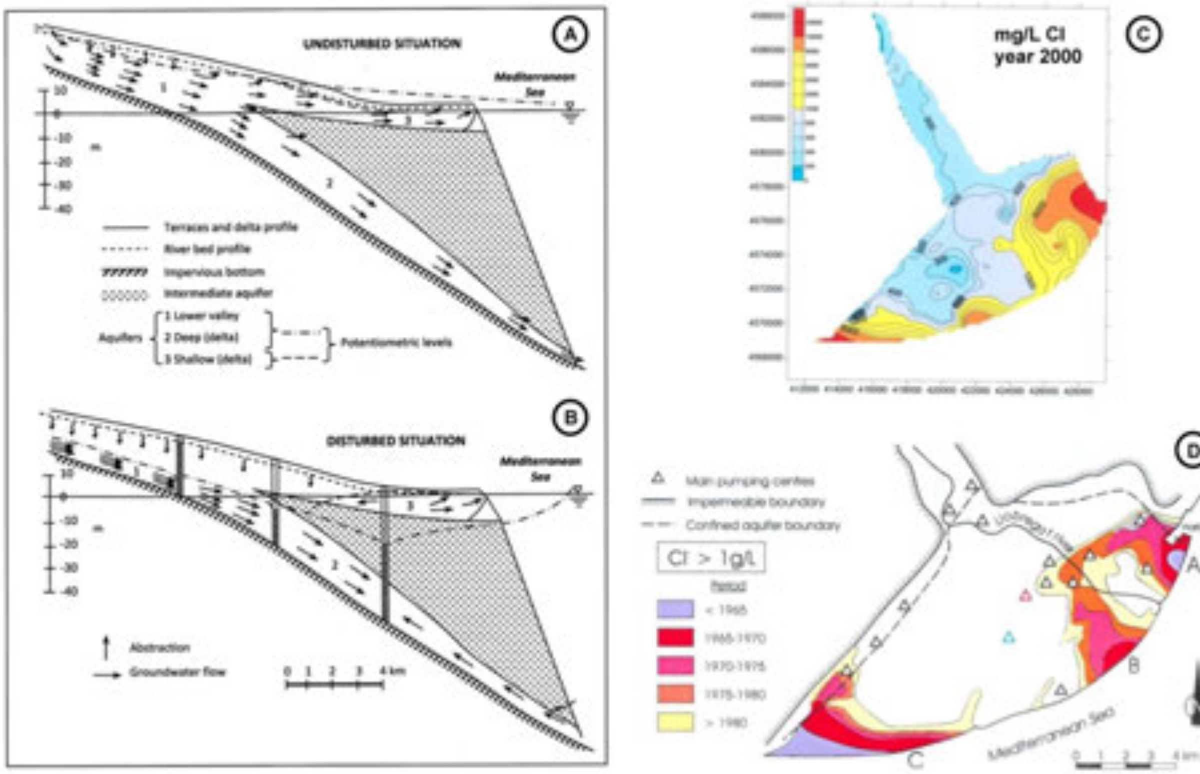


Figure 19. Loss of groundwater quality in the Llobregat River Delta, Barcelona, Spain, due to a combination of progressive sea water intrusion and recharge river water deterioration by potash mining upstream.

A) natural situation in the early 1900s; B) situation around 1975, when groundwater abstraction was at its maximum. C) chloride content in 2006 in the delta deep aquifer and the lower valley aquifer (after the Users' Community), which also shows the chloride pollution due to mining activities; D) advancement of saline contamination due to seawater intrusion in the delta deep aquifer (after Iribar and Custodio, 1991).

5.6 Groundwater quality related to mining

Mining is an important activity in many developing countries, but also in past or present industrialized areas, and often represents a main national income and a source of employment. It results in multiple point-pollution sources. Tailings, deep and open mine drainage, and mineral transportation and treatment are important sources of acid waters, dissolved heavy metals, salinity and some organics associated with fuel exploitation or used in mineral processing.

These are difficult situations from the groundwater governance point of view since sectoral institutions that are not sensitive about groundwater conservation issues may press to turn a blind eye to risks. Civil society groups are generally effective in introducing environmental responsibility and promote good governance, but this needs time. Clear advances have been produced to control the damage of large territorial activities and constructions, and to act soon after some large accident is produced, but small mining activities are much more difficult to control, thus action at municipal and groundwater users' associations' level is needed.

Oil extraction produces large quantities of salt water and brines, loaded with organics and some heavy metals, which are potential – and in most cases actual – groundwater pollutants. These waters are sometimes infiltrated in nearby aquifers, heavily contaminating them. It may be possible to inject this water, after treatment, into the exploited layers, but if not feasible, injection into other deep saline aquifers is practiced. Current and future leakages are a serious contamination threat to be considered in groundwater quality governance.

Salt mines pose special problems due to the high solubility of the minerals. Halite exploitation is often a rather controlled problem, out of natural leaching of salt outcroppings, since the product is sold or fully used in factories to produce common salt, chlorine and soda. The most important impacts are produced by mines producing potassium chloride – potash – from sylvite and carnalite. These salts need a processing that generate Na–Mg–Cl brines and a large quantity of halite and other salt wastes that are disposed in easily leachable, often poorly protected salt tips. The amount of halite wastes and other soluble minerals may be decreased by backfilling the abandoned parts of the mine, but there is always an excess that goes to tips. Classical examples are the Werra mines in Germany, the mines in Alsace, France, nearby the river Rhine, and those in the middle Llobregat and the Arga river basins in Spain.

Aquifers and rivers can be directly or indirectly heavily salinized. In the aquifers of the Low Llobregat valley, with an important recharge from river water, the chloride content background of about 80 mg/L before 1925 raised up to 600 mg/L in the 1970s when mining started, although it was then lowered to 150-200 mg/L after tight controls in the mining area and the construction of a pipeline to carry and dispose the brines into the sea (see Figure 20). The cost to society due to increased corrosion and poor water quality along many decades is not known, but surely high. Remaining high chloride content in river and aquifer water has recently imposed the application of salinity reduction by electrodialysis and reverse osmosis, at a significant cost to citizens.

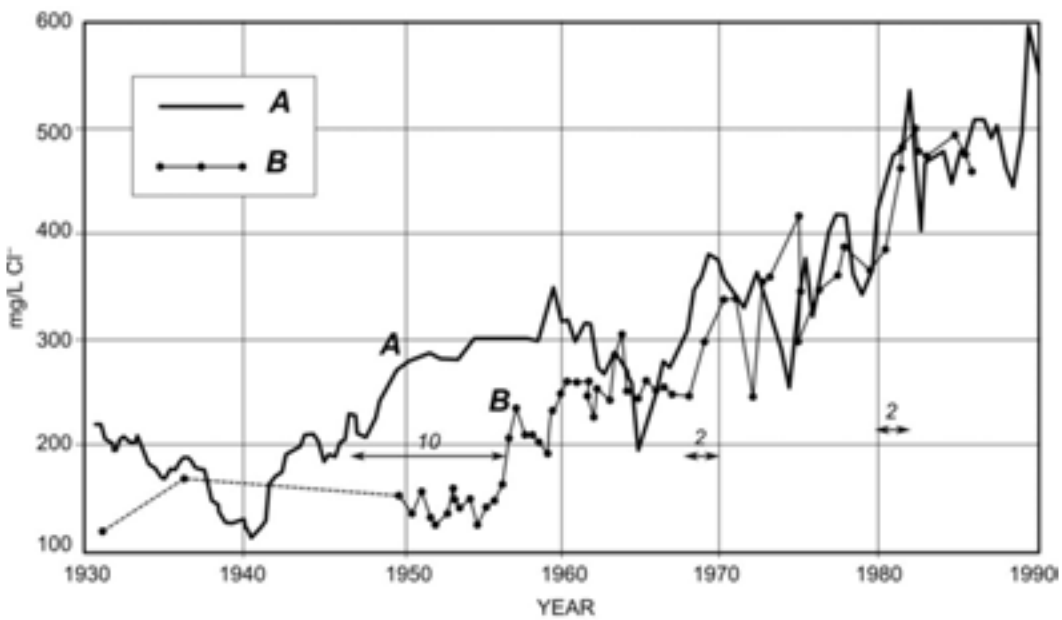


Figure 20. Evolution of chloride contamination in the Llobregat River lower valley, Barcelona, Spain, due to river water pollution, mostly due to upstream evaporite salt mining activities to produce potash.

Mining started in the mid 1920s, stopped from 1936 to 1939 during the Spanish civil war, and resumed afterwards. A brine–pipe constructed in the 1980s alleviated and halted new increases but has not fully solved the problem. Well A is just at the mouth of the delta and well B is about 4 km downflow, in the centre of the delta; in this small, highly permeable, and intensively exploited aquifer system (turnover time of about 2 to 3 years in the unconfined part) the transit time from A to B was about 10 years in the 1960s, and afterwards it reduced to about 2 year when exploitation was at its maximum, and currently is again about 10 years after abstraction reduction, well relocation, and piezometric level recovery.

Abandoned coal and sulphide mines get inundated with water. Near the water table, sulphide oxidation produces high acidity and metal dissolution, mostly Fe. Most of these mines are found in very low permeability formations but contaminated water often finds its way to local springs and aquifers. In the case of carbonate rock the pollution effect is partly tamed due to the pH being raised by carbonate dissolution, although the aquifer becomes contaminated, mainly by sulphate and earth-alkaline cations, but also by some heavy metals that form soluble carbonate complexes or remain in solution while the ambient is reducing. In nearby springs, Fe and Mn precipitate, affecting large areas, and wells extract Fe and Mn loaded water.

Highly polluted springs and rivers in metal mining areas, as those in southern Spain, may become a serious groundwater contamination problem when surface water infiltrates the ground in mountainous areas, especially in arid areas. This can be limited by careful mining operation, at a cost. Sulphide mining produces large quantities of sulphide-rich wastes, able to generate highly acidic waters. They are stored in sludge basins, some of large dimensions. They often leak and recharge local aquifers. Some serious breakdowns of such storage basins have occurred, although only a few cases have been monitored and documented in what refers to groundwater contamination and restoration. One such large accident happened in the 1960s in Arizona, near Tucson, and a recent one in Aznalcóllar, south-western Spain (Ayora *et al.*, 2001); this last one was reasonably well-controlled after intensive cleaning works, at a high cost, and a strip of land along the river was expropriated to avoid the use of potentially polluted groundwater containing heavy metals for drinking and irrigation purposes, and is currently an ecological corridor along the river to connect two ecologically important areas.

Mining for construction materials (cement, rocks, ornamental products, gravels and sands) are important activities near urban areas and populated areas. Many of them are practiced in river valleys by extracting and processing alluvium. These sites are prone to pollution due to the use of oils, the breaching of the soil cover and the inflow of surface water. However, the main risk is when the pits are later on filled with materials, such as demolition wastes or soils from others excavations – often called "inert" although they are really not –, and also with urban refuse and industrial wastes. This is not rare when controlled disposal sites are not available or too expensive, environmental control is poor and wastes are given to non qualified, uncontrolled and even suspected firms. This is a main concern around large towns, especially in developing countries.

Often mining is artisanal (informal), carried out by small groups that lack technical support and rarely care for the environment. They may produce serious pollution sources. In the case of minerals in alluvium and sediments (called *placeres*) large earth movements are produced and large volumes of terrain and wastes are exposed to air and water, thus accelerating oxidation and dissolution processes. Many of these activities are for gold mining, and to recover it quicksilver (mercury, Hg) is used to amalgamate gold. The resulting environmental pollution by Hg is a serious concern in many areas in Central and South America.

For old abandoned mining operations of very diverse kinds and size, the responsible person or entity to restore and redress damage on groundwater may not be found or may lack the required financial resources. In this case, society has to assume responsibility through public investments, mostly funded by general taxes. This may be unaffordable for poor areas, which often need not only external technical assistance but also funding.

In arid areas, such as those in the central Andean region, mining needs large water supplies for ore processing and transportation through pipelines, and often scarce local groundwater resources are used. It is not rare that these intra-montane basins are closed, ending in salt flats (called *salares*) in which brines form. The high density of brines favours an extensive deep layer of saline water (Figure 21) that easily spreads due to groundwater withdrawal for the supply of mining activities, thus producing salinization, accompanied by spring-flow decrease.

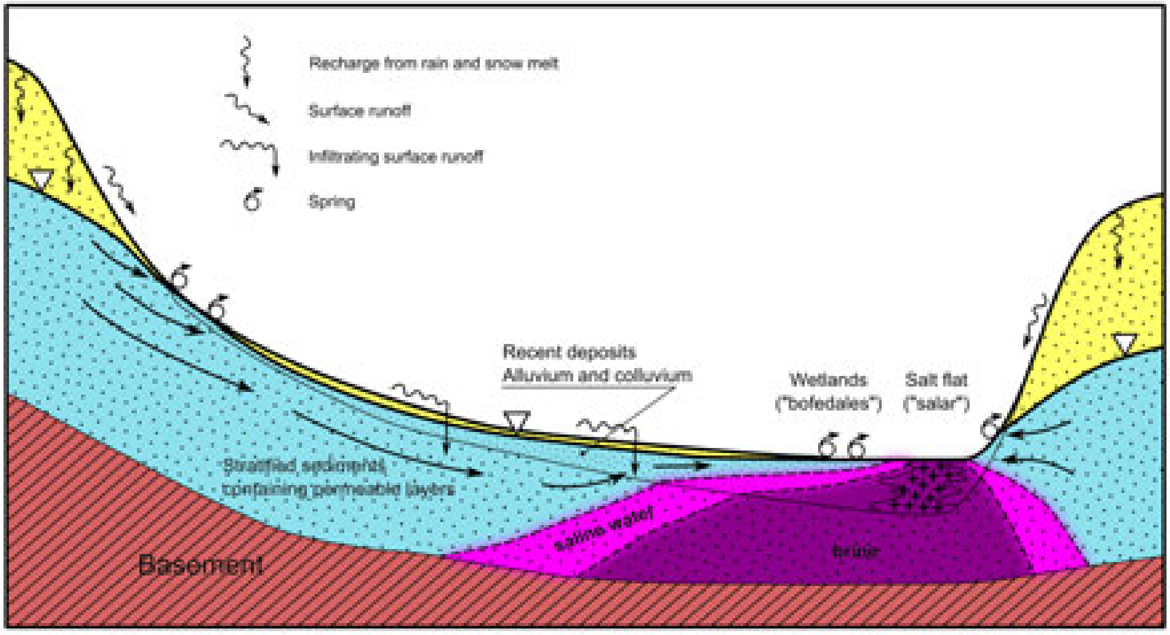


Figure 21. Schematic cross–section showing a closed basin ending in a salt flat ("salar") with surrounding wetlands. *Inspired in the high altitude, intramontane Andean basins of northern Chile. Dense brines tend to expand over a large area and are easily mobilized when groundwater is developed, especially following permeable horizontal displacement faults along these basins.*

Similar comments on groundwater quality governance as those in Section 5.7 apply. Action at municipal level is a key issue since this is generally the responsible level in many legal frameworks. However, large mining activities are of regional and national interest, being a source of large incomes and, in some cases, of widespread corruption. Governance needs clear legislation, political will, good information and training (both at central and municipal level), as well as means to deal with external pressure when supra-municipal interests are at stake. However, at municipal level norms have to be based on and supported by wider-scale legislation, an efficient justice and police system and political commitment.

5.7 Groundwater quality in areas subject to waste-water discharges

Urban and peri-urban areas, including associated industrial areas, are mostly subject to waste-water discharge. Groundwater conditions in such areas are rather different from those found in natural, rural and agricultural areas. Since land surface is compacted and largely paved, a common assumption is that rainfall recharge highly decreases and converts into surface runoff. This is only partially true since experience shows that recharge continues to be high and even greater than it was previously, mostly due to losses from water distribution and sanitation networks, irrigation of green areas and infiltration of local runoff (Chilton *et al.*, 1997; 1999; Foster *et al.*, 2011). This has a clear influence on local groundwater quality (Bruce and McMahon, 1996; Custodio, 1997; Vázquez–Suñé *et al.*, 1999). The issue is partly addressed in Section 5.1. Mining for construction materials is a related issue, as commented in Section 5.6.

Municipal wastewaters are characterized by high organic contents and some salinity increase with respect to supply water. This water may significantly contribute to aquifer recharge, especially in areas with old, poorly maintained sewage networks.

In poorly controlled areas, municipal refuse and urban wastes are often disposed by dumping into excavations, mostly sand and gravel pits. Local authorities often argue that if wastes are not in direct contact with the saturated zone, groundwater pollution does not occur. Albeit, rain percolates easily through the wastes since, in most cases, a true impervious cover is missing. This percolating water leaches solutes and organic matter in an often highly reducing ambient. Thus, water recharging the aquifer is often highly contaminated and possibly loaded with heavy metals, boron and poorly degrading and persistent organics, such as chlorinated solvents and mineral oils (see Section 5.1 for further details). A heavily polluted plume may develop and move down-flow, which sinks advectively into the saturated zone due to the flow-lines pattern, and sometimes due to buoyancy forces when there is a salinity/density difference. Some components decay anaerobically, producing CH_4 and NH_4, decreasing SO_4 and increasing Fe(II), until progressively less reducing conditions are found downstream and laterally, as the plume disperses and mixes with aquifer water. Some pollutants may disappear gradually due to natural processes, but often what is considered decay is really dilution.

In well-designed sanitary landfills, it is assumed that percolation is very small due to the stratification created by alternating clay layers, and what penetrates is drained for treatment. Unfortunately, this is not always the case, and what are called clay layers may actually be rather permeable and cheap local materials. Thus deep recharge is produced, and no or little leachate is collected, which is wrongly perceived as a good result that eases drainage water treatment. The aquifer below may become highly contaminated and after some time – often a short time in karstic and fractured rocks – may affect down-flow wells, springs and rivers. Local climate plays an important role in leachate composition. In some protected sanitary landfills, especially under dry conditions, the leachate may be highly saline and may contain high dissolved organic matter concentrations.

Industrial wastes are as diverse as industrial production is. The most polluting activities are paper mills, textiles, tanneries, mineral oil refining and chemicals and food processing. Small factories may pose a problem when poorly controlled – as is often the case – since they tend to dispose their liquid wastes by infiltrating them or dumping their solid wastes in excavations as filling materials. Especially concerning are small platting industries using chromates and other metals, often dispersed in peri-urban areas pits and backyards.

Many factories using, producing and disposing toxic substances move from industrialized areas to developing countries and poor areas, where environmental restrictions are loose, not enforced or just lacking. This is a serious concern for groundwater quality in these areas. Contamination may go unnoticed or concealed for a long time, thus creating difficult and long-lasting health and social problems, of very difficult and costly solution, if feasible at all.

Groundwater quality governance should include and address these issues, which may involve complex situations due to the many interests around. Often governance should rely on a higher level of decision and policy.

Part 2: Diagnostic

6 Constraints to Groundwater Quality Governance

Constraints refer mostly to groundwater quality governance and management limitations. In most cases, scientific and technical shortcomings are less relevant than institutional, human and economic ones, as commented in the following sections.

6.1 Constraints due to knowledge and monitoring

Basic science and technology are generally not a limitation for groundwater quality governance, but aquifer knowledge and their functioning under existing conditions, as well as monitoring of the relevant variables are. Monitoring is expensive and has to be suited to the actual groundwater quality and pollution problems to be addressed according to their relevance. Monitoring may be a serious constraint in many areas, especially developing ones, due to the cost of staff training, data processing and knowledge sharing with society, without which monitoring loses most of its intended impact. On the other hand, since monitoring is cheaper than many public activities and undertakings, investments do not attract the public and mass media, and also difficult to show, so it is politically and personally less rewarding. This explains why studies and monitoring do not have the consideration they deserve and are often subject to budget cuts when economic restrictions have to be applied. This is currently the situation in some aquifers of Europe, where in order to reduce expenses only what is expressly required by law is carried out. However, the existence of mandatory minimum requirements and their enforcement are an important step towards good groundwater quality governance. The adoption of compulsory minimum requirements and the availability of means to comply with them may be a challenging task in developing countries, but should be a clear objective to be accomplished, when necessary, with the help of external assistance.

Groundwater quality assessment often suffers from poor, incomplete and biased information. This is due to lack of representative sampling points, poor understanding of groundwater, scarce trained staff, insufficient financial resources and the localized nature of pollution sources. Natural and diffuse contamination is easier to detect than point pollution, due to the widespread effects it produces. However, its impact may appear slowly and highly delayed. In any case, knowledge of the vertical distribution of pollutants is a difficult task due to the general lack of dedicated deep sampling points. Currently, water samples from long- and multi-screened boreholes are composed of mixed waters from different depths – probably ignoring the deepest layers due to insufficient penetration and isolation. Consequently, during pumping to get a sample, water from contaminated layers is diluted with that of other layers. This produces a distorted and misleading image of actual contamination.

Transparency in action, programs, spending and accountability is appearing as a major issue to create trust and confidence, and its lack is often identified as a mayor constraint to governance. Experience is scarce and at most first steps are being done in a few countries, such as the USA, and such steps are seriously promoted in the EU, but still not fully developed. However, there is little practical experience in groundwater quality transparency.

6.2 Constraints due to staff

Groundwater knowledge, monitoring and management need specially trained personnel, not only hydrogeologists, but also experts from other branches, such as engineers, environmentalists, biologists, chemists, economists and lawyers. Moreover, trained technicians and field staff with good knowledge of the territory and of local institutions and people are essential. This is often a serious human and economic constraint in many cases in developed countries and a major drawback in poor developing countries. Education on groundwater quality governance should start at school level, as well as from specialized training and informative courses for medium and high level stages, with special emphasis on the local issues to be dealt with. Finally, employment stability of field personnel and the availability of sufficient operative means are key issues for groundwater quality governance.

6.3 Constraints due to institutional barriers on knowledge and action

Governance relies on government institutions, as well as on other institutions of the civil society and water users, with convergent goals and common interests. These institutions need adequate knowledge, sufficient staff, means to act and a legislative umbrella. Problems for groundwater quality governance arise when institutions do not exist, have poorly defined roles or lack sufficient resources. This is the case of many developing countries, but also of developed ones when institutions are weak, not interested in groundwater issues, sectoral, or politically controlled. But even with sound institutions, some barriers may appear.

Different institutional barriers hinder the knowledge of the contamination status and of pollution sources of an aquifer system. The lack of interest in groundwater issues is due to poor understanding of groundwater importance and of its long-term and delayed behaviour. This happens especially when people in charge of groundwater management are engineers trained in operation and management of surface water works, but not in groundwater management, water quality and governance. This is the case of the personnel of some traditional water authorities who are good professionals in their training fields, but not in the new responsibilities. It may happen that even knowing their limitations, they tend to act cooperatively and often reject other professionals to keep privileges or to preserve their jobs. Things become more complex when groundwater is privately exploited – legally or in practice – without due regulation. Often engineers, managers and decision makers – including politicians – erroneously assume that groundwater management is a 'private affair' that does not fall into the competence of public administrations, thus ignoring or neglecting surface water–groundwater relationships and the importance of groundwater itself. They rarely realize that a common pool resource of great social relevance is at stake and that issues affecting groundwater will eventually affect surface water as well, and *vice versa*.

Barriers are more severe when other water administration staff are involved, such as lawyers and economists, who are generally not aware of groundwater characteristics. Groundwater and its characteristics are often inadequately, erroneously or not at all considered in norms and laws. In most countries and regions, the poor consideration of long-term, delayed and progressive effects constitutes a major barrier that does not allow the adoption of appropriate governance arrangements to deal with groundwater contamination and pollution.

The above-mentioned circumstances are barriers that hinder the adoption of protection measures unless there is a specific legal mandate to do so. If no legal obligation exists, action is taken – when possible – only when the problem is noticed, which often happens when contamination is at an advanced stage of contamination. Further barriers are related to the different sectoral institutions that intervene: water, environment, housing, agriculture, forest, industry, tourism, land-use planning, transport, etc. These institutions are often poorly interconnected and have their own sectoral goals and priorities and they do not only often disregard the possible side-effects of their actions, but they also try to dominate the scene, disregarding other circumstances.

Good governance requires a higher-level coordinating institution and wide-scope legislation. Deviations and conflicts should to be solved as fast as possible by agreements, with the help of the coordinating institution, instead of resorting to administrative and civil courts. Even in developed countries, court decisions are commonly slow and often come late, when the problem has worsened and remediation has become costlier or unaffordable. In some occasions, a court may impose the halting of existing groundwater withdrawals until some quantity of quality problems that has appeared has been studied and documented and solutions drafted; this may become an added burden to groundwater developers and may worsen an existing situation.

6.4 Action to deal with groundwater pollution

In case of serious contamination impact, action should be taken, in particular to control the contamination source, although in some cases the source may have already disappeared or may have been modified earlier in time. Remediation is often required, but is a costly operation – hardly affordable in developing countries – that may lead to poor results if not carefully done. In certain cases, remediation is just unfeasible (Norris *et al.*, 1994; NRC, 1993, 1997, 2008; Pankow and Cherry, 1996; Barcelona, 2005). Remediation rarely works for diffuse pollution, except locally by enhancing and creating non-contaminated groundwater bodies through enhancing natural recharge or through artificial recharge or managed aquifer recharge (MAR) (Fernández Escalante and San Sebastian Santo, 2012).

For contaminated aquifers, the action proposed is often the abandonment of the aquifer for the intended use, although other uses may continue if they do not worsen the situation. However, action is needed to prevent further progress of pollution and the spread of contaminants. The abandonment of a given groundwater resource implies cutting on water demand or looking for other local or imported freshwater resources – generally at a higher cost – and the introduction of protection measures to preserve these new sources. In some cases, in-the-aquifer treatment or the construction of reactive barriers are possible actions for pollution abatement, but they are not easy to implement and operate. Costs are often high and failures are frequent. Advanced groundwater legislation – as in the USA (where EPA is the responsible authority) and in the EU – is generally against aquifer abandonment and requires remediation, but in practice implementation may be too costly or too slow. Thus, exceptions have to be admitted on grounds of disproportionate social and local costs. This is still a poorly developed area of water legislation. The situation may become critical when norms do not exist or are not applied, as is the case in many developing countries, thus creating these norms – and ensuring availability of the means to apply them – is an essential step for good groundwater quality governance.

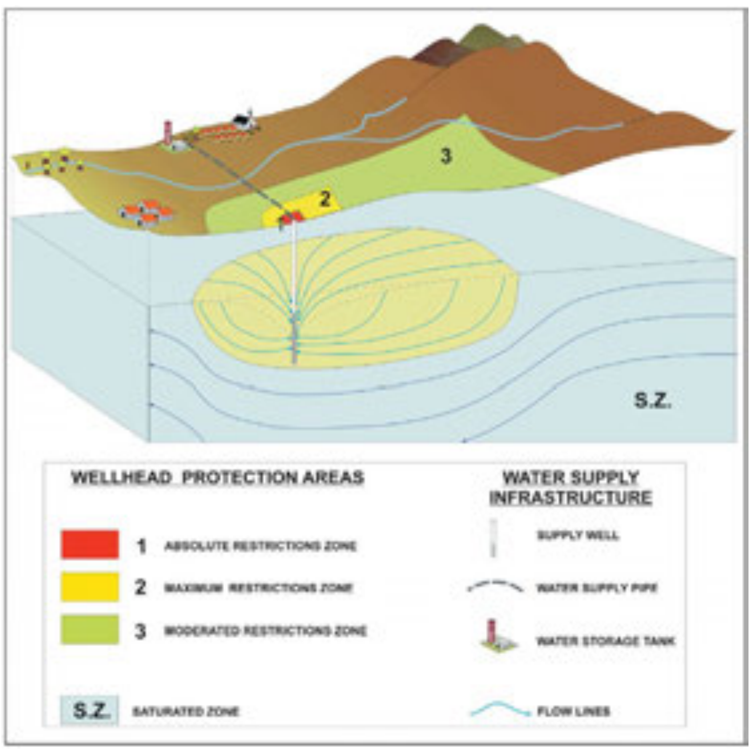
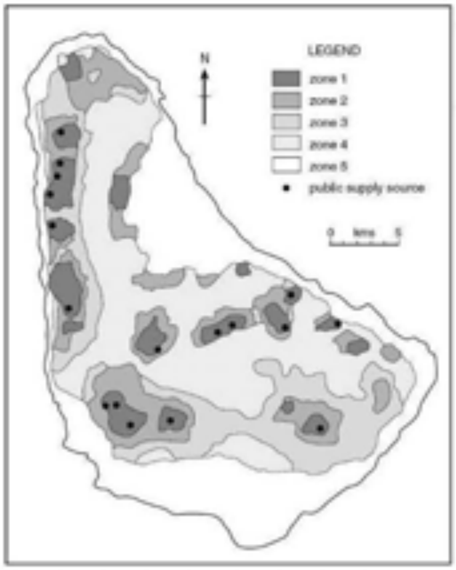


Figure 22. Schematic representation of well–head protection areas and their zonation (after Martínez Navarrete and García García, 2003).

6.5 Protection areas in groundwater quality governance

Protection areas can be defined for the conservation of drinking groundwater sources. In such areas, human activities are limited and special cautions are introduced to avoid contamination (Figure 22). Protection areas are provided for in the legislation of many countries, mostly in North America and Europe, where rules are established for the definition of such areas (Martínez-Navarrete and García-García, 2003). Methods vary from those based on hydrogeological maps to model-assisted methods, following conceptual developments (Foster and Skinner, 1995;

Matthess *et al.*, 1985; Hirata and Rebouças, 1999). The establishment of protection areas may involve restrictions on private property and on permitted activities. Consequently, their application and enforcement may become highly controversial and generate legal disputes between landowners and government institutions. The definition of a geographical boundary may become a challenging task, especially in karst and fissured rock areas. Limitations refer mostly to water-table aquifers. The application to confined aquifers is more complex and less experienced; it depends on groundwater transfer times and involves drilling norms, and their enforcement.



Zone	Definition of outer boundary	Maximum depth of soakaways	Domestic controls	Industrial controls
1	300 day travel time	None allowed	No new housing or water connections. No changes to existing wastewater disposal except when Water Authority secures improvements	No new industrial development
2	600 day travel time	6.5 m	Septic tank of approved design, discharge to soakaway pits. Separate soakaway pits for toilet effluent and other domestic wastewater. No storm run-off to sewage soakaway pits. No new petrol or fuel oil tanks	All liquid industrial wastes to be dealt with as specified by Water Authority. Maximum soakaway pit depths as for domestic waste (column 3)
3	5-6 year travel time	13 m	As above for domestic wastewater. Petrol or fuel oil tanks of approved leak proof design	
4	All high land	No limit	No restrictions on domestic wastewater disposal. Petrol or fuel oil tanks of approved leak proof design	
5	Coastline	No limit	No restrictions on domestic wastewater disposal. Siting of new fuel storage tanks subject to approval of Water Authority	

Figure 23. Example of groundwater protection areas in Barbados Island and explanations (after Chilton et al., 2006; Margat and van der Gun, 2013).

There are initial successes to define and enforce groundwater protection areas in some countries, like Germany and the United Kingdom. An example for an island is given in Figure 23. However, the establishment of new areas may prove difficult once people, social and private institutions and the public administration become aware of the limitations, costs and handicaps protection areas involve.

In many countries, the definition and the enforcement of protection areas have not progressed due to inadequate legislation, difficulty or incapacity to enforce restrictions – within and outside the public administration – and lack of means. The implementation of protection areas requires mobilization of important staff and economic resources to compensate for disproportionate charges and to maintain monitoring and control. This is difficult to carry out without close involvement of municipalities and groundwater users – not only those extracting the water to be supplied, but also the other aquifer users and stakeholders. Lack of social involvement and means explains the poor success of this management measure in many countries in spite of existing regulations. The number and dispersion of small supply systems renders the matter even more complex.

The establishment of protection areas for mineral springs and spas has been more successful, possibly for regarding often scarcely populated areas and for attracting powerful interests. Often such activities are under the responsibility of mining authorities, without involving water authorities. The former have traditionally been more successful in enforcing the rules, especially in Europe, but failures due to poor control are found in other countries, such as Argentina and Brazil.

6.6 Socio-economic constraints on groundwater quality governance

The main socio-economic constraints arise from the fact that neither the quality nor the quantity of water in nature are given any economic value, taking into account the ecological services provided and the opportunity costs, as is the case for many common goods. Water only takes on economic value once it has been appropriated for use, without considering its intrinsic worth in nature. Ensuring good quality of the appropriated water arises from the potential to trade it, at a sales price reflecting its quality. On the other hand, ensuring good quality for a common resource is problematic because the externalities referred to its use are not taken into account. Such are the need for adding treatment or the early deterioration of equipment.

The big challenge for good groundwater quality governance is to identify arrangements to claim externality costs while ensuring good quality. The EU Water Framework Directive obliges to take into account all costs, but this is still insufficiently developed in many of the member states, especially for agricultural uses. Government, institutions and society have to be aware that, because groundwater is important to the environment and the services it provides, its development affects them both. Economic evaluation is needed, although this is a difficult task. Economists have developed means for quantity and – less frequently – quality assessment of damage to ecosystems, although some basic issues are still under discussion (Esteban and Albiac, 2011).

Social constraints are important, such as the attitude of people and their institutions with respect to groundwater contamination. Having properly trained and empowered personnel, as involving groundwater users and stakeholders, are also essential. But the economic component is usually a dominant issue in most implementation processes. Resources are needed for adequate monitoring and data processing, to establish protection areas, to eliminate pollution sources or to find, develop and protect alternative water resources. They are also required for remediation, for public training and information, and for the support of users' involvement. Due to the lack of funds in developing countries, groundwater quality impairment is likely to continue leading to the progressive loss of their natural heritage. A serious and accepted technology to deal with these problems, as well as initial foreign funding or subsidies may be needed, but should not become a source of corruption or produce "wicked" results.

The effective application of the "polluter pays" principle in water quality governance relies on strong political will. It can be readily applied in urban and industrial environments, especially when water supply and sewage networks exist. However, the effective application in other circumstances may be difficult or unfeasible. Its application to groundwater and agricultural water use is particularly difficult, since the cause–effect nexus does not readily appear to people, and pollution appears delayed, progressive and difficult to be noticed early if adequate monitoring is not available.

A further problem is how make "polluters" pay for the damage they produce or will produce. Applying the collected fees and fines to improve knowledge, monitoring, aquifer conditions and the environment may induce payers to comply with new restrictions, as they feel their money is being correctly used and in their own benefit, instead of just supporting the burden of an increasing bureaucracy or used to pay for other unrelated purposes. With specialized technical and legal support, funds for the prevention and correction of pollution may be established – under existing water authorities, or specialized public or private institutions – with the contribution of taxes and fines paid by the polluters.

From a global point of view, strict application of the polluter-pays principle in one region may generate local socio-economical problems – probably less than the long-term damage from pollution, depending on the applied discount rate – and may favour the transfer of polluting activities to other regions with looser regulations. This happens as factory translocation to other more permissive countries and importation of foods.

Virtual water is the water that has been consumed in a given area to produce goods that are traded between countries or regions (Allan, 2009, 2010; Hoekstra and Chapagain, 2008), mostly importation of food, but also fibers and a large series of minerals and manufactured goods. "Virtual pollution" could be considered the water quality and groundwater quality loss due to the production of the traded goods. Virtual water trade is increasing worldwide and currently part of the economy of many areas is based on adding value to imported products that carry with them a large quantity of virtual water. This is an important issue in global and regional water governance, which involves groundwater quality aspects as well.

7 Scope for Securing Social and Environmental Benefits through Governance

7.1 Basis for groundwater quality governance

Impaired groundwater quality is a serious social and economic loss of water resources, ecological services and heritage. This may be more difficult to recognize and more pervasive than water quantity impairment, even in arid areas. To avoid further deterioration, it is necessary to remediate and protect what is still unaffected. Appropriate water and land-use management measures are needed, in the framework of well-prepared and accepted water management plans, and under clear and enforceable laws and norms. Groundwater governance must ensure the participation of civil society and stakeholders' institutions, which should co-operate and accept their specific responsibility.

Groundwater quality governance partly relies on direct action to control and reduce pollution (Table 3) and partly on "soft" action for prevention.

Table 3. Some methods for controlling pollution sources to be considered for groundwater quality governance

Pollution source	Possible control method
Landfills	Regulation of sitting, operation and closure Monitoring the site
Underground storage tanks	Periodic inspection Pressure testing Improved construction
Spill, leaks, improper disposal of hazardous wastes	Control of distribution and use Storage regulations Effective fining of malpractices Mandatory inspection of: ● transportation ● storage ● use Fast removal of spill damage Monitoring the facility
Agrochemicals: ● fertilizers ● pesticides ● herbicides	Introducing good agricultural practices: ● application limits ● timing of application ● application methods ● permits for use Ban dangerous substances Control the disposal of used containers
Feedstock wastes	For intensive farms: ● sufficient storage facilities ● document waste use and disposal ● control of pharmaceuticals use For extensive farms: ● Limits to animal spatial density
Septic systems	Regulation of ● sitting ● installations Periodic inspection Licensing installers

Governance of groundwater quality issues is highly influenced by the poor integration of groundwater users and other stakeholders, and by the poor coordination among water authorities, regulators and those responsible for the environment. This is a key issue for securing social and environmental services and for hindering negative actions, but there are some peculiarities about groundwater compared to other water resources. Aquifers occupy a large territory that supports dispersed human activities, economic and social interests, traditions and practices, often supplying a large number of groundwater users.

A first step in governance is to assure that users and institutions understand that common interests are at stake. The aquifer is a common-pool water resource and heritage, a source not only of water but also of ecological services to be preserved to a reasonable extent, in a win-win mode. Governance is needed to make the common benefits explicit. Based on this, new steps can be taken. Top-down actions are seldom effective since groundwater users tend to be suspicious about the final goals of government's and top level persons, and thus try to avoid compliance. It is not rare that they hide and withhold information, and even cheat, especially when they suspect there is political manoeuvring and alien personal interests, their rights may be cut down, or new taxes and charges are expected. Building institutions is a necessary second step. Involved agents have to understand the slow, delayed, long-term behaviour of groundwater, and act accordingly.

The subsidiarity principle – a basic principle in the EU – should be generously and effectively considered, besides other governance principles, when they apply: equity, solidarity, participation, prevention and precaution – to avoid large or irreparable damage, but without a paralysis through analysis. The subsidiarity principle states that what can be better done at a lower level, closer to society and individuals, should not be done a higher level. Decentralization should be promoted as well as staff training and qualifications. Concentrating decisions and power in high administrative levels, particularly when unqualified, leads to widening the governance gap – especially when referring to groundwater quality –, thus increasing mistrust, giving a poorer social service by cutting on benefits and increasing costs, and leading to a progressive and often irreversible loss of natural values and their associated services.

Groundwater quality governance is deeply related to and relying on groundwater ethics – including moral and religious principles –, a modern subject in development (Llamas and Delli Priscolli, 2007; Llamas *et al.*, 2009; Custodio, 2010b) and an UNESCO and IAH priority subject.

7.2 Monitoring for groundwater quality governance

Good monitoring is an important issue for water governance, and especially for groundwater quality. Without reliable data it is not possible to understand and value real situations and make reasonable forecasts on the evolution and the involved economic, social and political costs. Produced data have to be retrieved, treated adequately and made available and usable to regulators, decisions-makers and stakeholders. Many recent and effective tools are available. There is wide body of scientific and technical knowledge (Everett, 1987; Condesso de Melo *et al.*, 2007; Rouhani and Hall, 1998), although local situations and economic and human resources play a key role. This is the case of the Doñana National Park aquifer system, in south-western Spain (Manzano *et al.*, 2009).

Even if good data retrieval technology for monitoring is available, a main problem is the need to cover a large territory, with a rather low sampling and measuring frequency. This is quite different from surface water. The need for trained teams and for a large number of boreholes and observation points spread over a large territory make monitoring expensive, especially for deep aquifers. In the case of point pollution of groundwater, the cost is high due to the need of a dense monitoring network able to follow the pollutant movement, which often needs a 3-D point of view and the support of some modelling.

Sampling may be simple or expensive, although the appropriate technology is generally affordable. Obtaining reliable and representative water samples is key to good monitoring. Existing wells and boreholes and large springs generally yield a groundwater mixture whose interpretation may be difficult and may lead to biased results. Well-trained personnel is needed, with the advice of senior hydrogeologists.

Well-trained and adequately equipped institutional staff is needed for surveillance and maintenance. For groundwater quality, this is often a heavy burden that the authorities may successfully share with trained local people, entities and communities, cooperating as part of their duty to preserve groundwater quality as their heritage, even if using simple methods.

There are many water quality parameters to be considered for monitoring. A what-to-do list should be tailored to each case. Many of these parameters are rarely obtainable automatically, and need in-the-field sampling and in-lab analytical capacity. The required measurements need to be carefully designed to reduce costs and personnel. A common practice to save money and effort is using easy-to-get proxy and lumped water quality parameters to detect changes, but some studies are needed to show they are able to yield the wanted monitoring results.

Groundwater quality monitoring is generally focused on single aquifers. This is often enough but in some cases monitoring has to be extended to other related aquifers, aquitards – e.g. for saline water bodies displacement or inter-aquifer pollution transfer – or the unsaturated zone – e.g. to follow downward movement of diffuse pollution or the depletion of non-aqueous separate phase pollutant accumulations (NPLs), such as oil and organic solvents. This detailed monitoring is expensive and needs specialized teams, but is often needed for groundwater quality remediation and management. Unfortunately, this is an expensive activity for poor areas that often proves difficult to implement. In some cases undertakings that have the capacity to control the groundwater contamination produced by them, try to not comply by using legal subterfuges or by corrupting officials. A large governance effort is needed to redress this, when this is the case.

To make people aware of local groundwater being naturally unsuitable or inconvenient for some uses, and especially for drinking and food processing, specific information must be made available to them. This should be prepared carefully to call the attention and promote action, but avoiding undue alarm and irrational rejection. Education is important. Information is needed to progressively introduce the basic knowledge and understanding of real risks, how to avoid them, and the alternatives compatible with current situations. These tasks are not easy and need communication specialists who understand the problems, know how to explain them to laymen, and are able to achieve co-operation and involvement instead of confrontation. There are some experiences in different countries, such as Mexico, India, Bangladesh and Argentina.

7.3 Institutions and users' involvement for groundwater quality governance

Governance depends on effective institutional relations between the government and the users. When institutions do not exist, a first step is promoting them. These institutions, both authorities and participatory ones, make government action more effective (Hanak *et al.*, 2011), especially in groundwater management, and improve relations with users (Pahl-Wostl *et al.*, 2008). Well-designed institutions are needed to avoid administrative slowness and other legal hindrances, as well as to facilitate adaptive evolution (Hanak *et al.*, 2011). However, institutions are not always successful in groundwater management (Howe, 2002), particularly in what refers to groundwater quality. Failure is mostly due to inadequate or unenforced legal framework, economic constraints and behaviour of persons at the top decision level.

The need to involve governmental institutions in groundwater management is a current subject of debate. The Gisler–Sánchez effect (Gisler and Sánchez, 1980) shows that these institutions are not needed and that the same final economic results are attained under unrestricted competition. This refers mostly to groundwater quantity under unbounded conditions, but in most real cases limits have to be taken into account, and then some extent of governmental control is advisable to reduce social costs (Esteban and Albiac, 2012). No detailed studies taking into account groundwater quality and the related externalities are known. Since there are clear restrictions, public control should probably appear as the optimal solution.

The dialogue between water regulators and groundwater users has been and is often poor or inexistent. This is partly due to water regulators being poorly involved in groundwater issues, especially on what refers to groundwater quality. Another reason is the existence of many dispersed and unrelated groundwater exploiters – a large number of wells –, often unaware of groundwater quality problems or at most having a myopic vision of reality. In many cases, top-down public information campaigns and discussion forums at local level – more rare – are the easiest way for the water administration to make contact with small groundwater developers and users, while direct contact is more likely in the case of large water supply companies and municipalities in charge of their own supply. To solve this lack of links, groundwater users should be organized and have democratically elected –following local rules – and trusted representatives. Currently, this is a difficult task due to lack of experience, individualism, mistrust and poor knowledge of users. Information on existing problems and on possible solutions is required to raise awareness about the need to protect aquifers as a common heritage. Collective action is especially needed to control non-point pollution (Esteban, 2010).

Creating the conditions to involve groundwater users is time-consuming, as local practices must be honoured. The task should be conducted bottom-up instead of being the result of often suspected and rejected top-down decisions and regulations. However, should public support be needed at the start, it should be provided discreetly. Good examples are the several decades old experience in California (Box 5), and more recently that of Arizona, USA. Other successes already exist (Custodio, 2010a), with different backgrounds and tailored to local situations and interests, as in Mexico (Guerrero, 2000; Foster *et al.*, 2004) (Box 6), India (Knegt and Vincent, 2001), and Spain (Aragonés, 1995; Codina, 2004; Hernández-Mora *et al.*, 2010) (Box 7). It is important that these institutions act transparently and pursue clear and agreed goals. Otherwise they may lose a large part of their potential, as is the case of part of the numerous Groundwater Technical Councils in Mexico (Webster *et al.*, 2011), in which federal government, local authorities and users' goals are poorly related, and users representation is often biased toward large corporate groups.

Box 5: Groundwater governance institutions in California dealing with seawater intrusion

In California, landowners have the right to extract as much groundwater as can be put to beneficial use. The State cannot directly manage groundwater according to the California State Water Code. Agencies, adjudications and districts have been created under special legislation to allow users to manage groundwater inside their boundaries. Currently there are 12 districts, not all of them involved primarily in groundwater quality. Tasks vary from agency to agency, from monitoring to limiting extractions, including water imports to alleviate nitrate pollution and seawater intrusion problems, or to agree in exporting groundwater to other areas.

Orange and Santa Clara Valley Water Districts have carried out and operated aquifer recharge facilities in which imported water, and in some areas highly-treated municipal waste waters, are upgraded to drinking water standards, and then stored underground, partly to mitigate seawater intrusion problems.

The Los Angeles County Water Replenishment District has a long experience in operating artificial recharge facilities and seawater intrusion barriers since the 1960s, in order to improve conditions in the Central and West Coast basins.

At any administrative level: county, region, state or country, the number of groundwater representatives should be limited due to operative reasons. The higher the level, the wider the representation should be. This means that local users' associations have to agree on being part of progressively larger groups. In fact, in Spain, the current national users' association, that mixes interests in groundwater quantity and quality, was recently given a seat in the National Water Council and participates in a number of River Basin Water Councils.

Water authorities are often reluctant to the establishment of users' associations, either because they fear it could decreases their power and decision capacity, or simply because they are not trained in communication and social sciences and shared decision-making. This is an important barrier that has to be overcome to achieve governance. Updated laws and regulations are needed and have to be enforced to foster groundwater users' self-regulation (López-Gunn, 2007).

Box 6: Collective groundwater for governance: the COTAS of Mexico

The central region of Mexico has a large population, well-established irrigated agriculture and important industrial developments. Groundwater is crucial for supply in the 192 000 km^2, high altitude, partially closed basin on the Lerma-Chapala river basin, in a semi-arid environment. It extends over five states, including the Federal District of Mexico and the State of Guanajuato to the north. There are about 100 aquifers that are considered over-drafted.

In order to foster better groundwater management at the local level, with more stakeholders' involvement, the *Comisión Nacional del Agua* (CNA, National Water Commission) promoted and supported civil society organizations called *Comités Técnicos de Aguas Subterráneas* (COTAS, Technical Groundwater Committees) in 1992, with the goal of helping to address local groundwater resource management. About 70 COTAS were created. A few can be considered successful but many others lack appropriate support from stakeholders since they are 'suspicious' of the hidden goals of public administration initiatives. However, the COTAS are a notable leap forward to attain aquifer governance after the problems derived from the early development stages. Their full success needs to also consider groundwater quality, since nitrates are dramatically increasing in many areas. Some areas are experiencing great pressure from a groundwater quality governance point of view, especially around the Chapala Lake, which receives waste water from Mexico City and produces drinking water that is at risk.

Box 7: Groundwater users' communities – Governance experience in Spain: the Lower Llobregat case

The development of groundwater for irrigation started late in the 19th century and mostly in mid the 20th century, often carried out by individuals or small groups sharing expenses. This led to a rather uncontrolled aquifer development, with scarce public regulation after the 1879 Water Act, since groundwater was considered a private affair.

To try to cope with groundwater intensive development, preserve the benefits and correct drawbacks, groundwater was declared in the public domain by the 1985 Water Act, which required new groundwater developers to obtain a concession from the corresponding Water Authority. Already existing groundwater users were given the option to remain just as they were. Groundwater user communities are recognized as public entities for collective management of aquifers. Currently there are more than 1 400 groundwater users' associations registered, and hundreds of others organized as private corporations, but they are mostly for sharing water and manage irrigation networks, and so they cannot be considered as institutions for the collective management of aquifers, except a few ones, and groundwater quality is not their main concern.

The top-down creation of *Comunidades de Usuarios de Aguas Subterráneas* (CUAS, Groundwater Users' Communities), even the compulsory ones in the areas legally declared as overexploited have been largely a failure. However, those created bottom-up to solve actual problems or to have a voice in public water management do well and are highly efficient. Currently, 20 groundwater users associations have been formed and are active, or are close to start, and a fast expansion is foreseen. Each association is tailored to the specific situation of their area. They are dominated by irrigation interests and have a limited interest in groundwater quality, except for those in coastal areas. A Spanish Association of Groundwater Users was established for mutual promotion and assistance.

The first Groundwater Users' Community was that of the Lower Llobregat aquifer system, close to Barcelona (Catalonia, north–western Spain). Groundwater dynamic storage, mostly in the valley, is up to about 200 km^3. The detailed hydrogeological studies carried out from the 1960s by the Public Water Administration were made known to groundwater users, who decided to cope with existing and foreseeable problems, largely due to quality issues. As a consequence, in 1975 a Groundwater Users' Community was created, well before groundwater was declared in the public domain, in an area in which aquifer management already existed and groundwater quality was an issue due to the high river water salinity from the salt – potash – mines upstream, from large industrial and urban pressure and from seawater intrusion, besides increasing costs.

The Water Authority and the Users' Community, that includes the main water supplier, have been active in monitoring, studies, and action on pollution sources. Now brines and saline water upstream are collected in pipelines, wastewater treatment has been improved, uncontrolled disposal of wastes has ceased, and artificial recharge continues to be carried out since the 1950s. The result is that groundwater quality has improved. The intensive aquifer development produced groundwater levels below sea level, in the important delta deep aquifer, starting a serious seawater intrusion, first detected in 1965. Many salinized wells were abandoned – although others continued to be operated for industrial cooling –, thus helping to slow the seawater intrusion process. The current extraction decrease and the increased artificial recharge are improving the situation. In 2007, a well barrier to control and redress seawater intrusion was constructed to inject into deep wells deeply treated (including reverse osmosis) municipal wastewater (Ortuño *et al.*, 2010).

Most of existing institutions dealing with groundwater issues are found in semi-arid areas with intensively exploited aquifers, dominantly for agricultural and livestock purposes, where water quantity is the main concern, and water quality issues are only marginally addressed or ignored. One exception is the Lower Llobregat aquifer system groundwater users' communities (Box 7), mainly dominated by suppliers and industrialists, where groundwater quality problems are derived from river and environmental pollution and from seawater intrusion (Custodio, 2012). There, the Water Authority and one of the users' communities are currently working on a freshwater deep injection barrier to reduce and control seawater intrusion (Ortuño *et al.*, 2010). Groundwater quality management is well developed in coastal Southern California, since decades ago, and seawater intrusion is an important issue for some of them. These are specialized institutions for groundwater resources management, besides those of the state and the counties, which operate within the framework of an integrated water resources management plan that binds governmental institutions.

A sometimes complex combination of top-down actions and bottom-up initiatives is needed. The assumption is that governmental and related institutions have a wide-scale and integrated point of view, while single users have the local knowledge but with a restricted vision focusing on myopic interests. Thus, as conflicts arise, institutions may provide a space for dialogue and facilitate dispute resolution in a non-compromised environment. Governmental decisions and actions are more effective when agreed upon. Groundwater governance experience is scarce and recent, especially for groundwater quality.

8 Rationale for Slowing Down, Halting and Eventually Reversing Degradation of Water Quality

8.1 Costs and discount rate considerations

In most cases, groundwater in aquifer systems is considered as having no economic value. Economic evaluation of water costs and benefits is carried out under this assumption, and at most some externalities are included, if any. This does not reflect the true value of groundwater, which includes the ecological services it provides and the opportunity value. There is scarce experience in the social/ecological evaluation of groundwater – an important issue for governance. A first estimation can be roughly obtained through the value of lost services. Intangible values, such as those related to local people feelings, social acceptability and preferences, and sentimental and religious issues have to be taken into account and integrated in a transparent way in governance arrangements.

Evaluation is all the more difficult when dealing with groundwater quality. Groundwater pollution implies a loss of usable water resources with an alternative cost, impairment of water uses, including irrigated crop yield decrease, and increased expenses for water quality correction and for aquifer remediation.

Costs and benefits have to be considered over a long period of time due to the slow behaviour of aquifer systems. To compare them, costs and benefits have to be cumulated after being discounted at a given rate to a given moment. The value of this discount rate is a subject of debate in social and economic forums, and inside the institutions that carry out the studies. This involves social, ethical and ecological points of view. Low discount rates increase the value given to the future. This means that the current generation saves economic resources and invest to benefit future generations, which are assumed to live under similar circumstances as today. However, in the future, science and technology may be quite different from current ones, thus partially invalidating the effort of present savings. High discount rates just do the contrary and favour the transfer of part of the economic burden of current activities to future generations; it is expected that future generations will be able to deal with water problems more efficiently than does the current generation and will benefit from progress made by the current generation through the intensive use of natural resources. This implies the acceptance of some degradation, loss of resources and quality impairment. All this involves ethical principles and behaviour and is perceived differently according to the general economic and political conjuncture. The long-term discount rate is different from the interest rates applied by banks in a given moment. Besides the perception of the value changes from times of good economic circumstances to moments of economic crisis, as is the current case in the USA and the EU.

In general, rich areas favour the use of high discount rates. Besides what has been explained, this is partly at the expenses of the poor areas producing part of the goods, which try to survive by sacrificing part of their heritage and overcharging future generations in exchange of possible future improvements, technology transfer and assistance. This is especially significant for groundwater quality. Ethics should inform management and governance decisions. The economic aspects of groundwater contamination are still an emerging field of economy. There are some evaluation attempts (WIR, 2004), but how to apply them need to be developed for practical applications, especially for developing countries.

In the urban environment, the value of water and its quality is rarely understood by the population, who often has a blurred – if not erroneous – idea of the origin of water and of the problems and costs involved. When domestic supply is permanently guaranteed and people do not suffer the effect of droughts – which is a goal for governments and supply companies – water is given for granted and considered a right. People are often unaware of the need to periodically increase prices to obtain more costly new water resources, to ensure maintenance and substitution of infrastructure – especially when this has not been done properly in the past – and to secure and improve water quality. Besides, politicians typically fear a loss of votes if they allow prices to increase. Awareness about the value of water should be promoted through public education, information, transparency and involvement in water supply affairs, and this is badly needed for governance.

Experience varies significantly worldwide, but the temptation of transferring costs to the future appears when there is a sustained economic crisis. To avoid this, bold government action supported by regulations is often necessary, even at a political cost. Under most circumstances, fuel, electricity and gas price increases are eventually accepted by citizens, but not for water and sanitation, and this is mostly due to poor information and communication, as well an insufficient transparency and citizen participation, which allows protest groups to appear.

A limited inquiry regarding some European groundwater-related institutions and users yielded mixed results: a number of users declared themselves as uninterested and not willing to pay for improvements; others found the issue to be concerning (Custodio *et al.*, 2007). However, in some European countries, people are worried about water quality – especially groundwater quality – and consider that chlorinated water is unhealthy, thus requiring that groundwater be directly supplied to the tap. But in other areas people prefer to resort to bottled water for drinking and cooking, which, on a monthly basis, is often more expensive than the tap water price increase they are unwilling to pay. This attitude denotes mistrust towards public supply companies, considered as being unable to guarantee safe and good quality water, although this may not be currently the case. In addition, the issue of emerging pollutants is just appearing, which will affect current demands and preferences for drinking water.

8.2 Rationale to control groundwater quality impairment

As explained in previous sections, groundwater quality is an important characteristic that limits water use for the intended purposes. Thus, groundwater quality impairment through pollution may mean a loss of available freshwater resources or the need for water treatment before being used. The loss of resources has often to be compensated by the development of additional local, imported or new water resources, at a cost. Also water treatment has a cost – sometimes a high one – depending on the kind of pollution and its intensity. In both cases, the physical and economic burden is charged to users, who are generally not the ones causing the pollution and only receive a small part – if any at all – of the benefits produced by activities that cause pollution.

Given the characteristics of aquifers, polluting activities and actual groundwater pollution may not occur simultaneously, as the latter may result from past activities that were carried out even decades earlier. Similarly, the effect of current activities may not appear before decades in the future. This means that large volumes of water in the unsaturated and in the saturated zone may be polluted in a given moment, with turnover times of years to centuries, depending on local circumstances and pollutant characteristics, such as sorption and decay.

The generally admitted statement for surface water resources that controlling pollutants at the source is socially – and often at private level – cheaper than dealing with the consequences, is even truer for groundwater. The cost of restoring groundwater quality is generally higher than that of avoiding pollution at the origin, even considering the discount rate to be applied to values accrued in different times. Detailed studies are scarce or incomplete. Economic data on aquifer restoration after point pollution events show that high costs are involved, and often with limited success.

8.3 Risk assessment and norms in groundwater quality governance

Risk and risk assessment are important for governance. Fundamentals have not been developed until recently (NRC, 1989, 1994 and 1996; Covello and Merkhofer, 1993; Haines, 1998). Following common understanding, hazard has to be distinguished from risk. A hazard is a phenomenon or an activity that can cause adverse effects, such as using contaminants in an area overlying an aquifer or drilling through protective soil. A risk is the likelihood that a hazard really causes its adverse effects, together with the measure of the effect. Risks can be caused by real phenomena but can also be the result of human or societal perception (Müller, 2010). Actual harm – damage – may occur as a consequence of risk, and may vary according to the system's vulnerability. It involves qualitative and quantitative measuring of the probability of an adverse effect, such as the actual infiltration of a contaminant in the ground or its release from a storage site, and its presence in groundwater or in water pumped from a well at a given concentration. Measurements and data are rather uncertain.

Risk assessment of action or of lack of action in groundwater quality issues is a poorly developed area, in spite of the large economic resources and financial expenses involved, and the possible loss of water resources and heritage. In what refers to groundwater quantity, mathematical models help to evaluate scenarios to study possible failures, problems and associated costs. However, many of the parameters to be used are poorly known and calibration with observed reality is often impossible due to insufficient temporal and spatial monitoring, and the changing economic and social conditions. This is even more difficult for groundwater quality. Except for conservative solutes and major ions scenarios, results may be highly biased and uncertain, even worthless, and cause–effect relationships – taking into account the delayed and slow behaviour of groundwater – are seldom available or estimable from case studies and previous experience.

Very simplified unchecked assumptions have often to be introduced for groundwater quality risk assessment. Evaluation of risk in environmental management, including groundwater quality, is currently based on coarse assumptions and the opinion of experts. Besides considering risk assessment based in careful and supported studies – where they exist –, regulatory frameworks are often the result of social and lobbies' pressure, reflecting a compromise reached among social organizations, ecological groups, mass media and politicians, within their political goals in a given moment.

In what refers to the application of the EU Water Framework Directive, risk has other meaning, since it refers to the probability of achieving the established goals at the established dates. There are guidelines on the evaluation of the likelihood of failing to meet the objectives (Scheideler *et al.*, 2008). This is also relevant for groundwater quality governance inside the EU, besides the administrative and legal implications. 'Risk assessment' is considered a forecast of the future at different scales, while current situation analysis is called 'status assessment'. The application of risk assessment to groundwater quality needs a sound understanding of aquifer system behaviour, based on a validated conceptual model. The evaluation is done through a tiered process (Müller, 2010): (i) qualitative risk screening for groundwater bodies (pre-assessment) – in which they are classified into three categories (not at risk, information uncertain and at risk) –; (ii) appraisal or semi-quantitative assessment, after investigation and data collection; and (iii) characterization and evaluation or risk assessment (at risk or not at risk) through further investigation and data collection. This goes in the direction of decreasing uncertainty. This is followed by a second-cycle characterization and risk assessment.

Norms are usually based on general principles such as no further deterioration, reversing trends and recovery of polluted aquifers, as in the case of the EU Water Framework and Groundwater Directives, now incorporated into the Water Acts of the EU Member States. Target dates for accomplishing goals are needed, as well as how to deal with special situations and how to define groundwater quality baselines and the minimum monitoring that is needed. This approach seems to be producing quite good results in the European Union. However, this is partly due to these norms being supranational regulations with the capacity to apply sanctions to member states that do not comply. Something alike happens in federal countries, as in the USA, but not always, depending on the power and means of federal institutions and on states' laws. This is much more difficult inside a given state or region, especially when legislative and judicial powers are not truly independent and often become politically and socially controlled. Under these circumstances groundwater quality governance seems a difficult task that needs previous reinforcement and changes in the legal framework, as well as in the ability of the government to enforce it.

The EU directives are important and compulsory for member states having yielded part of their sovereignty, and they involve important economic, administrative and social efforts to preserve and restore the environment. There are good results, but also failures and still many on-going activities related to groundwater quality preservation, control and improvement. The balance is reportedly positive for many countries, particularly thanks to the governance opportunities offered by efficient top-level institutions, which are in charge of implementing EU legislation at the national level. However, some analysts find some weak points that point to a too powerful Commission and a weak Parliament, and some bias in the orientation due to not all members being able to put forward their own interests. However the balance is positive, even for those that complain of not adequate consideration of their peculiarities. The USA has a different approach, but the two systems have points in common. However, it is not sure that these approaches can be directly transferred to other countries since local circumstances and capabilities may substantially differ.

State level norms, when applied to a large territory, often do not consider the variability of local circumstances and the existence of special situations. Thus, some regulated flexibility is needed. Also, groundwater quality norms and laws at state level are generally not based on detailed prospective studies, real risk, and socio-economic evaluations. This is currently an almost impossible and uncertain task, heavily dependent on the physical, economic and social circumstances found at the local level. Mid- and long-term objectives should be applied taking into account the changing socio-economic environment. To be effective, periodical updating of norms is needed. They should have an end date, with carefully designed steps for substitution or deep revision, starting well before the deadline. Otherwise, as often happens, norms become outdated and unrealistic and are thus loosely applied, often becoming a burden to society. Thus, norms may hinder proper action by institutions and open the way to chaotic behaviour, in which groundwater quality is often the big loser. All these issues have to be taken into account for groundwater quality governance.

8.4 Aquifer vulnerability to pollution assessment for governance

In groundwater science, the risk of diffuse contamination is evaluated by multiplying the vulnerability to pollution by the quantity of contaminant released to produce a concentration. Vulnerability to pollution is an abstract concept that qualifies or quantifies the susceptibility of an aquifer to be attained by a pollutant once it is on the surface (Margat, 1968; Foster, 1987; Adams and Foster, 1992; Vrba and Zaporozec, 1994; Robins, 1998). This is a debated concept, not easy to be used in practice but widely applied in institutional and university environments. Figure 24 is an example. Although there are no absolute values, several methods to grade vulnerability are available. Some are relatively simple and can be applied in areas with scarce data – e.g. GOD (Foster and Hirata, 1991; Foster *et al.*, 2002). Others are more data demanding, such as DRASTIC (Aller *et al.*, 1997) and SINTACS (Civita and De Maio, 1987). There are numerous efforts to compare methods and to adapt them to specific pollutants (Colman *et al.*, 2005; Conell and van den Daele, 2003; Worral and Kolpin, 2004; Ramos Leal *et al.*, 2012). Since the 1980s and mostly since the 1990s, a large effort has been done in many areas to produce vulnerability maps, which are intended to assist in decision-making. Such maps do not provide readily available local answers, which need accurate assessment at detailed scale by experts, an aspect that is not always understood by planners, water authorities and decision-makers.

However, vulnerability does not mean pollution risk. Groundwater contamination has to be measured in real terms, e.g. for a given contaminant, under current conditions and concentrations or quantities (EC, 2004), which is rarely done. Low vulnerability does not necessarily mean low risk when the contaminant load is high, and high vulnerability may imply no risk at all if there is no contaminant source. Vulnerability is an intrinsic value of a site or an aquifer (intrinsic vulnerability). There is an unbounded time dimension implicit in the definition of the concept under the designations of susceptibility of the aquifer being attained by a contaminant, and the contaminant penetrating the aquifer.

For a given pollutant or groups of pollutants, specific vulnerability can be defined. Specific vulnerability depends on the contaminant, and soil processes have to be considered in some way. Degradable and radioactive contaminants decay with time – the more exchanged or sorbed they are, the more they decay – and may reach concentrations below thresholds. Stable concentrations will eventually arrive, although they may be diluted and delayed; in the meanwhile, they cumulate in the aquifer until an equilibrium between inflow and outflow is attained. This is a common situation for salinity and for nitrate in an oxidizing ambient.

Despite the limits to the usefulness of the vulnerability approach, it is an interesting exercise for aquifer quality protection, and consequently for groundwater quality governance. However, real data is needed, but may not be available in many areas, especially in developing ones. The use of probable average values after a literature search and comparison with other cases is risky and often tends to smooth results, thus making zoning rather useless.

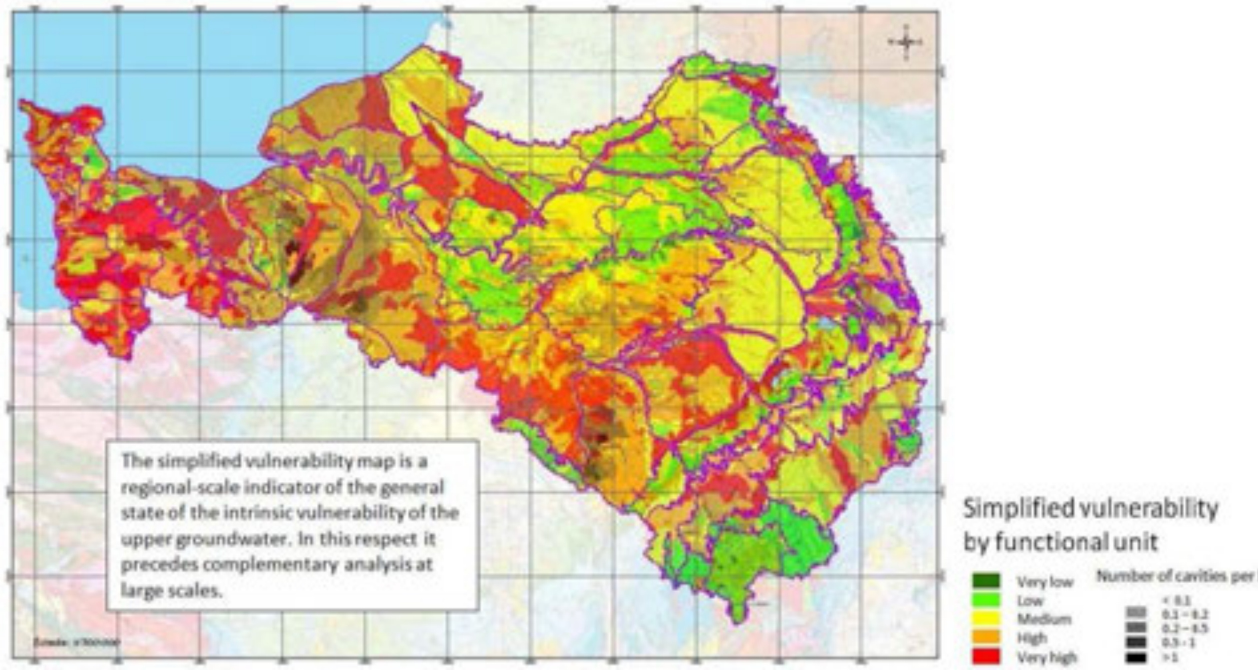


Figure 24. Map of intrinsic vulnerability to pollution of groundwater in the Seine–Normandie Basin, France (after BRGM, in Margat and van der Gun, 2013).

Details and usefulness for groundwater governance increase the more detailed is the scale is, but more data is needed.

Part 3: Prospects

9 Prospective on Groundwater Quality and its Governance

9.1 Projected evolution of groundwater quality trends under no action

One possible scenario for groundwater quality is no action under current circumstances, that is to say, no further activity directed to influence contamination and pollution of groundwater, out of what is already being done under current legal pressure to reduce pollution, existing pollution sources and socioeconomic circumstances. This varies from country to country.

Salinity increase and nitrate build up are of special concern. Under current groundwater development circumstances, salinity increase will be a growing concern in coastal areas, especially where alternative water resources are not easily available, as well in continental aquifers where saline water exists in aquitards and deep seated layers, or where irrigated agriculture produce saline return flows –the more efficient irrigation is and the higher irrigation water salinity is, the higher the production of saline return flows is. River, spring and aquifer salinity is expected to increase below new deforested areas in the dry belts. This may mean increased water demand for irrigation to compensate for the decreasing crop yield and to leach the soil as irrigation water salinity increases.

The erroneous – although widespread – assumption among water regulators and managers that aquifer exploitable resources are equal to recharge will certainly lead to salinity increase in many areas of the world, as well as to increased natural and artificial contamination due to excessive water level drawdown, besides other impacts on other water resources, the environment and the territory (Llamas and Custodio, 2003). Determining and agreeing on the right aquifer development is part of its governance, depending on actual physical, administrative, legal and social constraints and on what the society asks, in a mid- and long-term perspective. These constraints are variable over time and should be taken into consideration, given the slow behaviour of groundwater.

Nitrate build-up is and will continue to be a serious concern with the current trends in agriculture and food production, and with non-sewered sanitation practices in urban areas. In many aquifers, nitrate build-up happens, even if there is no more pressure, when the steady state has not yet been reached after past disturbance. Other major groundwater quality problems are more local. Arsenic is a growing concern as groundwater development intensifies in many areas of the world. The increase of fluoride is of concern as deeper groundwater is being used, especially in volcanic areas and in areas affected by fine volcanic ashes.

Expanding urban areas in poor countries entail an increase in the number and size of local pollution points, such as wastewater discharge points, refuse disposal areas and burial of wastes in pits. Problems related to salinity, nitrate, possibly soluble iron (Fe(II)), hardness and mineral oil are likely to grow, as well as contamination from domestic chemicals and wastes from poorly equipped and unconcerned small industries. Water-table fluctuations in response to recharge events will produce pollution peaks as wastes and contaminants in the unsaturated zone will be more readily mobilized.

When widespread groundwater contamination forces to look for new supply wells in new areas or when existing wells are closed down as others water sources are made available, there is a water-table level recovery that may mobilize contaminants held in the unsaturated zone, mostly mineral oils, non-aqueous liquids and slowly-degrading organic matter. This worsens groundwater quality and affects the remaining wells in operation – often domestic-supply wells. This is a serious problem around many large cities, especially in slum areas, as in the peri-urban areas surrounding Buenos Aires, the “Conurbano Bonaerense”, Argentina, where there is a continuous shallow aquifer.

The widespread use of caffeine, nicotine, pharmaceuticals, antibiotics, body care products, domestic cleaners, endocrine disruptors, and psychedelic drugs is growing, both in developed and developing areas, although the involved chemicals may be different according to local living standards. Many of them degrade slowly or are recalcitrant and thus cumulate, which means they will be predictably added to groundwater in increasing concentrations. Being only partly degraded in wastewater treatment processes, they are likely to reach downstream aquifers. These emerging contaminants still have a poorly known effect on population at the low concentrations they are commonly found. This is a growing concern, not only in rich areas, but also in poor areas where some contaminants are used in similar quantities and sanitation systems are not functioning. However, in poor areas other groundwater contaminants are currently more concerning since they affect health more immediately. While in some rich areas people are asking for untreated groundwater at home – aquifers have to be maintained unpolluted –, in other areas, there is no alternative to the use of poor-quality groundwater and the priority concern for governance in the short run is avoiding further deterioration rather than improving quality.

It is difficult to make an assessment of contamination by pesticides and fertilizers used in agriculture, as well as antibiotics and other substances used in feedstock, both in developed and developing countries. Such substances have evolved from very persistent and highly retained products, such as the widely used in the past DDT (dichlor–diphenil–trichoroethanne) and lindane (hexachlor–cyclohexane), to more active, specific and degradable ones, although some of them result rather mobile in the biosphere. A trend toward increasing contamination by these substances and their metabolites seems to be the rule. In some cases, however, it is unclear whether they actually increase or they are more frequently found due to the continuously improving sampling and analytical methods and to the increased availability of well-equipped laboratories. Remobilization of the more persistent chemicals held in the soil may happen when there is a land-use change, but this is poorly known.

Impairment of groundwater quality by pollution from mineral oils, fuels, chlorinated solvents and other non-miscible products seems to be decreasing, in frequency and intensity, in many areas of the world as a result of improved technology and standards to avoid leakages and unsafe disposal, of more effective enforcement of regulations and of improved monitoring. But this may not be the case in developing countries, where the pressure toward economic development dominates the scene and is often accompanied by further point-pollution events and aquifer quality deterioration.

Groundwater quality governance largely depends on social understanding and conscience of the need to protect aquifer from pollution. In some areas of the world, protection and restoration measures have been adopted. However, in many other areas further groundwater quality deterioration will have to occur before corrective action is taken. Groundwater quality governance arrangements must provide an adequate framework and the means to promote action before degradation goes too far.

9.2 Prospects for better management of groundwater quality trends

Improved governance of groundwater quality trends relies on three legs:

a) Legislation on water resources management, land-use and other related aspects, and the means for effective enforcement and updating.
b) Adequate monitoring and information exchange – results should be made easily and readily available to all concerned people,
c) Cooperation and shared responsibility among groundwater users, civil society and local authorities in the control, protection and surveillance.

Direct management measures consist of:

a) halting active pollution sources – this refers to: sound use of chemicals and care of wastes, including mineral oils and organic and chlorinated solvents; leakage correction; safe disposal of wastes; adequate use of agrochemicals; good management of feedstock wastes; protection of storage sites for hazardous fuels, chemicals and agrochemicals; transportation of dangerous substances on safe routes; and early action as soon as a leakage is known;
b) providing controlled and effectively operated waste disposal sites;

c) identifying old pollution sources, with plans to assess the associated hazard and to clean out, restore or confine contaminated sites, as required;
d) introducing sound design of wells, boreholes and drilling practices, and adopting standards for drains, drainage tunnels, dewatering systems, public works that affect soils and aquifers – including protection against inter-aquifer leakage, isolation from surface and from poor quality aquifer layers, and prevention of the effect of deep saline groundwater;
e) making groundwater development compatible with quality protection;
f) protecting and enhancing aquifer recharge, and considering the possibility of artificial recharge when it is really needed;
g) providing instruments to know aquifer vulnerability and define protection areas for supply groundwater;
h) limiting seawater intrusion by controlling groundwater abstraction, timing and pattern, combined with increased aquifer recharge and barriers – when they are advisable, possible and affordable – such as freshwater injection and saline water abstraction;
i) introducing barriers to limit the spread of some pollutants, both passive (impermeable, reactive) or active (pumping and recycling, injection);
j) taking out deposits that contain polluting substances to a controlled dump site, to be buried or discharged on the surface;
k) operating *in situ* groundwater treatment facilities – there are different kinds – as a tailored but costly and slow solution.

The list is not complete. It includes actions that are progressively more complex, costly and sophisticated. The first ones are generally affordable, although they imply a cost and need enforceable norms, but the last ones may require high investment and difficult-to-obtain expertise. Thus, they are rarely suitable to developing areas.

For groundwater quality governance, due consideration should be paid to the fact that cleaning polluted aquifers and restoring polluted sites is generally a long-lasting affair, with unsure results (Anderson and McCray, 2011). It is not easy to decide when a cleaning process is accomplished. A common situation is that after the cleaning process is assumed to be finished – contaminants in abstracted water or air are below thresholds – later on pollution re-appears as contaminants held in low permeability bodies diffuse again to the aquifer.

Another way of dealing with groundwater contamination, which is neither the best nor an environmentally desirable one, is just by accepting that the aquifer is contaminated and treat abstracted groundwater adequately before use. The feasibility of this approach depends on the type and degree of contamination, as treatment is costly and may require sophisticated means. Over time, when costs are discounted and added, it may result in a large economic expense.

In groundwater quality management, the alternative between controlling and addressing pollution at the source and treating the polluting water afterwards is often posed. Avoiding groundwater pollution by acting at the source is cheaper but complex and needs the joint action of several government sectors with different goals, which often requires a higher or external level of decision. In addition, such preventive action does not solve currently existing pollution problems, as many of them were caused by activities carried out a long time ago. It is an investment for the future that might not be attractive for short-minded politicians without pressure from the civil society. At some point, a decision has to be taken to avoid further deterioration and, at the same time, deal with inheritance, which is costly and perhaps a poorly rewarding activity. It is affordable in moments of economic bonanza, as when the EU Directives were drafted, but not so clearly under the current economic crisis. This means that groundwater quality governance has to be able to adapt to the changing economic and social conditions, which may influence the way the present and the future are valued.

The question of who pays the costs associated to pollution is related to the above considerations. Treating and controlling the pollution source charge the cost to the potential polluter – indirectly to people through increased prices of goods – and may deteriorate producers' ability to compete in free markets. The cost of treating polluted water is charged to groundwater exploiters (increased operation costs), to groundwater users (increased prices) and to society (increased taxes), with possible complexities when public funds are applied as co–payments or subventions, often wicked subventions if they last, since they may produce a counter-effect.

Indirect or 'soft' measures are as effective as direct measures. They may not solve existing problems but may be useful to prevent further deterioration. They include:

a) raising awareness of the public, decision makers and managers on the value of groundwater, the cost of degrading its quality, the large expenses needed for restoration – if feasible at all –, the cost of what is irreversibly lost, and the methods of protection. Awareness raising measures should involve schools and include public forums, training courses, conferences, posters and videos;
b) adapting the institutions to new tasks for which they are not prepared. This means training staff, incorporating new trained people and providing adequate financial and technical means, which is not necessarily costly when compared to other common expenses;
c) improving monitoring, processing information and data, and making them easily available to all interested people. This may be accompanied by action to encourage people to study the information and data and to make proposals;
d) providing institutions and users' associations with means to carry out surveillance and to correct deviated or criminal behaviour. This needs some well-trained staff, a suited department or office, and the cooperation of local police;
e) reinforcing courts in order to have specialized teams and public prosecutors to deal with groundwater pollution and the impairment of ecological services. They should be able to speed up court decisions and guarantee compliance.

9.3 Prospects for engaging well users, regulators and technology providers in water quality improvements

In many areas of the world, hydrogeology and groundwater knowledge are becoming more common, at least among users and water authorities. Important efforts on regulation are being made. But this is not the common situation worldwide. Further effort is needed. The role of UN agencies, universities and associations, such as the IAH and the Association of Groundwater Scientists and Engineers of the National Ground Water Association, USA – the latter with special regard to groundwater quality – are opening new grounds and making groundwater users, regulators and engineers more aware of groundwater. However, many important groundwater properties, especially the large water storage associated – meaning long-term behaviour – and water quality issues, are still poorly understood, even in areas with a good tradition in groundwater use and management. This is a serious handicap to be overcome and a major hindrance to understanding what is actually occurring, how to deal with problems and how they may affect current and future generations. This knowledge is needed to raise awareness of the fact that groundwater is a common heritage and that environmental services are valuable and need preservation. Up to now, insufficient knowledge has prevented major advances in the joint or collective action of groundwater users, regulators and engineers, although there are encouraging achievements in understanding the basis of groundwater quality governance.

Groundwater quantity issues in semi-arid and arid areas are relatively easy to be understood, and agreement on joint action may be easily reached, although discussions may sometimes generate serious fights and rivalry. However, quality issues are more pervasive and difficult to identify and address, due to their slow appearance and delayed manifestation, to the scarcity of available data and to their invisibility, except for some dramatic cases. To make people aware of groundwater quality issues and of the need to participate in groundwater governance, more effort is needed. Some short-term results have to be obtained, shown and explained, in order to introduce the most important long-term ones, which are more difficult and costly to deal with.

Regulators – water authorities – are becoming more aware of the need to deal with groundwater quality improvements issues, at least because in many countries this is now a legal mandate. But they can do little if local people and stakeholders do not support them and cooperate with them. Prospects for engaging water users, regulators, engineers and technology providers in improving groundwater governance depend heavily on obtaining good results in diverse areas that represent different typical situations. These groundwater quality governance examples are currently very scarce. Efforts should be done to indirectly promote and help bottom-up initiatives from local people who understand the problems, may act as leaders and are able to make efficient use of the resources that can be provided. Engineers and technology providers have been mostly interested in complex issues and sophisticated methodologies, which are good for research, rich areas and powerful companies. However, in most common situations, simple and affordable techniques may be successfully applied for evaluation, monitoring, protection, remediation and management.

The prospective for these simple and affordable techniques is unclear, partly because possible markets are still too small and short of economic resources, and partly because water authorities have been reluctant – and still are – in expending on groundwater quality. Solving groundwater quality often offers less political reward than solving groundwater quantity issues, which are short-term, thus wanted results. The short-term goals of the often politically-controlled water authorities is a serious hindrance for progress, as well as the mass media preference for negative news instead of giving long-term positive messages. Groundwater quality problems and deterioration are badly acknowledged and accepted, since they create alarm, they are difficult to be solved and results – if attainable – appear late. Consequently, they are often concealed or down-played. In order to avoid this, regulations need to be enforced, the transparency rule must be applied and civil society is to be involved. Unfortunately, in many countries civil society is poorly organized or unwanted by the often less competent political society. Good governance has to create the appropriate environment for civil society to develop and grow.

Education is needed at different levels, although it is an investment for future generations. It is especially important in rural areas where locals should play an important role in protecting and managing groundwater quality.

10 Conclusions

Groundwater quality is, in many areas, a serious concern that will increase in the future. Concerning aspects are salinity, inadequate chemical composition and the presence of inconvenient and/or harmful solutes, organics, mineral oils, organic solvents, degradation substances and emergent contaminants. Saline water encroachment and/or up-coning is a growing problem in coastal areas, near saline lakes and as the result of three main situations: the widespread existence of deep saline aquifers in many areas of the world, the presence of return irrigation flows in dry areas or the transformation of natural forest into cropland and grassland in semi-arid and arid areas.

In semi-arid and arid countries, water quantity problems tend to dominate over quality, although this will probably change in the future, as groundwater resources become more stressed, aquifer functioning is growingly modified, human activities increase, better health conditions are introduced and the economic situation and living standards of people improve, as well as the increased knowledge and availability of monitoring data.

Groundwater quality is an important part of water governance. The main issue is related to poor awareness of the problem, on the regulatory side, on the groundwater users' side and within the society in general, which is also due to the often slow reaction and long delay of cause–effect behaviour that is characteristic of aquifers. Delayed effects are poorly sensed and understood, and may involve the transfer of part of the burden to future generations, to the same extent that we are currently observing what previous generations did.

Groundwater quality governance examples are currently scarce, in part due to the recent history of groundwater intensive development. An important role is played by the not-so-recent large land-use-intensive activities and changes, as well as by the recently introduced large variety of potentially polluting chemicals and agrochemicals.

For groundwater quality governance some issues and facts are basic premises to be considered:

1. The aquifer system functioning has to be known – conceptual model –, which includes groundwater- surface water interactions and the highly delayed and progressive changes of groundwater.

2. Groundwater quality and pollution are the result of many different factors, involving diverse government and social sectors, besides water; they have to play their role in groundwater quality governance through agreed action or as a consequence of decisions from a higher hierarchical level.

3. Land-use changes may produce important impacts on groundwater quality.

4. Water quantity issues may currently dominate in many areas, but quality issues will soon become relevant and have to be urgently addressed.

5. How groundwater is captured and exploited may greatly influence its quality. Wells and other groundwater wining works should be properly constructed and maintained, subject to norms and licensing, and follow periodically updated and agreed groundwater development plans.

6. Data on groundwater and its quality, as well as adequate monitoring are needed for governance, and results have to be made available to all interested sectors.

7. The cost of degrading groundwater quality may be high for the developer, the user and society; it may involve important externalities and the degradation of environmental services. It may also affect future generations and, in many cases, restoration may be economically unfeasible. Thus, protection of groundwater from contamination is generally cheaper than treating polluted groundwater – now or in the future – or than looking for new freshwater sources to replace what is lost through pollution.

8. Groundwater quality governance is the responsibility of governments, but they have to act jointly and with the support of civil society institutions, users and people. Effective action requires specialized institutions and participation of the often numerous.

9. Institutional barriers to groundwater quality governance have to be identified and corrected, inside a framework that represents social needs in a broad space and with a mid- and long-term vision. A needed goal is transparency.

10. Laws and norms are needed, and should be periodically reviewed and updated. They have to be enforceable and enforced, with the support of politically independent government agencies and courts.

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Conjunctive Use and Management of Groundwater and Surface Water within Existing Irrigation commands: the Need for a New Focus on an Old Paradigm

Digest

Communities vulnerable to unpredictable and unreliable water supplies in many parts of the world rely upon irrigation as a means of increasing food and fibre production. However, population growth within the developing world and increasing access to global markets for agricultural production, have been a driver for increasing irrigation demand such that water availability commonly constrains production. Pursuit of alternative water sources is often the first response to shortfalls in catchment yield, with prospects for improved efficiencies (production per unit volume of water available), considered only when other options are exhausted. However, even where improvements in system or application efficiencies are sought, potential benefits from integrating the management of all the available sources of water are seldom considered. Such benefits include optimising productivity and equity in the management of the total water resource irrespective of its source and promoting sustainability within an economic, environmental and social context.

The outcome of adopting a planned approach to conjunctive management is an operational model that approaches the optimal capture, storage, abstraction, system and on-farm irrigation delivery of all water sources, and the management of surface and sub-surface drainage, and so contribute to achieving sustainable economic, social and environmental outcomes.

Conjunctive use of groundwater to supplement surface water supplies is common in many parts of world, however integration is generally incidental, arising from spontaneous actions rather than being an outcome of a robust planning process. Under the "spontaneous" approach, irrigators opportunistically decide whether to source their water needs from groundwater, surface water supplies, or a combination of both, with their decision influenced by factors such as short-term resource availability, costs of delivery to the crop, tradability of unused allocation and water quality. Such farm scale conjunctive use has the potential to provide benefits to some individual irrigators in the form of reducing costs and increasing productivity and profitability, but does not optimise the economic, environmental and social benefits for the system as a whole (and hence all users). Such higher level objectives are the benefits sought from central planning of the total water resource as indicated above.

As surface water and groundwater are in most cases considered by both managers and users as separate resources with policy and management evolving in response to resource development, institutional and governance arrangements have within most states also evolved separately. The effect has been the establishment of 'boundaries' within the existing policy, statutory and regulatory framework that apply to the management of surface and groundwater resources. These boundaries are problematic as adoption of a full conjunctive management model is dependent upon a single integrated institutional framework and a robust governance structure that incorporates authority, accountability, transparency, stakeholder participation in planning and regulatory/compliance arrangements.

Re-structuring institutional arrangements so as to build governance within the context of a fully integrated conjunctive management framework requires commitment within the highest levels of government. Such a commitment is essential to instigate the reforms required to bridge legislative and policy gaps that are likely to lie between agency regulated and managed canal based systems, and the legacy of unregulated access to groundwater that dominates in most states around the world.

Upon instigating institutional reforms, governance arrangements are required that are able to apply a sound and robust policy/planning base founded in sustainability principles, with robust implementation/delivery mechanisms to achieve on-ground outcomes. These include:

- a consistent policy and legislative framework associated with both surface water and groundwater entitlements that:
    - recognises any unique attributes associated with a specific entitlement, but also provide trading mechanisms so as to enable the market to support the highest economic uses of water.
    - provide statutory power to government or a delegated agency to administer and regulate on behalf of the government.
    - Includes accountable and transparency in the decision making processes with mechanisms in place supportive of natural justice such as enabling appeals against decisions to be independently reviewed.
- a compliance management framework.
- mechanisms to instigate voluntary irrigator behavioural change (market instruments, direct incentives, extension).
- recognition and commitment towards the participation of stakeholders in the planning process, and provide advice to institutional agencies on issues associated with implementation.
- cost recovery models that provide a sustainable recurrent financial resource base to sustain institutional capacity for planning and operations over the long term.

There are a range of possible aspects to conjunctive management such as Managed Aquifer Recharge (MAR), natural hydrological connection between surface water and groundwater resources, supply integration, water quality management and drainage management. Key aspects to these opportunities for conjunctive management are as follows:

- MAR enables surplus surface water to be captured (during high flow events) and utilised at times when the dam or streamflow is depleted or when water is required for other purposes.
- Understanding of connectivity is critical within the context of resource assessment and water accounting, most importantly recognising that groundwater pumped from a connected surface water system will induce increased leakage from the stream or canal system reducing the volume of available surface water.
- Supply integration enabling groundwater to provide a supplementary source to a canal based system, that smoothes out the supply/demand balance either across seasonal patterns of water availability, or across decadal variability in climate. Such integration may involve groundwater distribution to the public canal system, although in most irrigation systems, such integration normally occurs on farm, as groundwater abstraction infrastructure is commonly privately owned with the pump located close to the irrigated area.
- Management of the quality of applied irrigation water such as accessing an alternative supply if the primary source is poor quality, and/or mixing surface and groundwater supplies to achieve an overall acceptable water quality for application to crops.
- Integration of farm drainage either by surface drainage networks returning water to the irrigation canal system, or sub-surface drainage systems that control land and water salinisation and water-logging, through either groundwater abstraction and re-use or salt disposal.

Planned conjunctive management presents an opportunity for significant benefits to be realised in the management of canal-based systems that are supplemented by groundwater resources. Such benefits arise because of the complementary characteristics of surface and groundwater water resources; characteristics that through planned integration of both water sources collectively will contribute to improved economic, social and environmental outcomes.

Whilst some sovereign states will continue to pursue new ‘green field’ irrigation developments based upon new dams or further groundwater development, within a generation, the growth in such initiatives, and even maintaining existing levels of development are likely to be challenged by water supply and ecological decline. Accordingly, it is necessary to recognise the constraints posed by our physical environment and consider conjunctive management as a means of achieving more with less.

Whilst poor understanding of the technical aspects of conjunctive management may be an impediment to adoption, it is the absence of integrated institutional and governance arrangements that is likely to be the greater barrier to progress. Institutional structures, policy objectives and regulatory powers must be enabling so as to achieve a holistic approach to water resource and irrigation system management for the collective good. Without such institutional and governance arrangements, the economic, social and environmental potential that lie within state and communities water resources will not be realised.

Thematic Paper 2

CONJUNCTIVE USE AND MANAGEMENT OF GROUNDWATER AND SURFACE WATER WITHIN EXISTING IRRIGATION COMMANDS:

THE NEED FOR A NEW FOCUS ON AN OLD PARADIGM

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1 Introduction

Conjunctive use of groundwater and surface water in an irrigation setting is the process of using water from the two different sources for consumptive purposes. Conjunctive use can refer to the practice at the farm level of sourcing water from both a well and an irrigation delivery canal, or can refer to a strategic approach at the irrigation command level where surface water and groundwater inputs are centrally managed as an input to irrigation systems. Accordingly, conjunctive use can be characterized as being planned (where it is practiced as a direct result of management intention – generally with a top-down approach) compared with spontaneous use (where it occurs at a grass roots level – generally with a bottom-up approach). The significant difference between unplanned and planned conjunctive use, and the approach governance must take to maximize the potential benefits from such use, is explored within this paper. Where both surface and groundwater sources are directly available to the end user, spontaneous conjunctive use generally proliferates, with individuals opportunistically able to make decisions about water sources at the farm scale.

The planned conjunctive use of groundwater and surface water has the potential to offer benefits in terms of economic and social outcomes through significantly increased water use efficiency. It supports greater food and fibre yield per unit of water use, an important consideration within the international policy arena given the critical concerns for food security that prevail in many parts of the world. At the resource level, groundwater pumping for irrigation used in conjunction with surface water provides benefits that increase the water supply or mitigate undesirable fluctuations in the supply (Tsur, 1990) and control shallow water-table levels and consequent soil salinity.

The absence of planners and of a strategic agenda within governments, to capitalize on the potential for planned conjunctive use to support these needs, is generally a significant impediment to meeting national and international objectives as they pertain to food and fibre security. There is an urgent need to maximize production within the context of the sustainable management of groundwater and surface water. The challenges posed in some ways reflect the evolution in objectives and management approaches that have been, and remain, common to irrigation development throughout the world.

Many existing irrigation commands source their water supply from both the capture of catchment runoff and aquifer systems. Typically, water has been sourced from either surface or groundwater supplies, with the primary supply supplemented by the alternative source over time. Accordingly, governance settings, infrastructure provisions and water management arrangements have emphasized the requirements of the primary source of supply, inevitably requiring the "retrofitting" of management approaches onto existing irrigation commands to incorporate supplementary water sources over time. Optimizing the management and use of such resources, which have been developed separately will in some situations require substantial investment in capital infrastructure and reform of institutional structures. Put simply, planned conjunctive use is relatively simple with *greenfield* (or new development sites), but significantly harder to achieve within existing hydro-physical and institutional/social systems.

Whilst these challenges and the associated benefits of a strategically planned approach are well understood and the subject of numerous reports on conjunctive use management, the current status of water management and planning around the world suggests that little has been achieved in its widespread implementation. This paper explores the reasons underpinning the apparent poor approach to full integration in the management and use of both water sources, and the absence of more coordinated planning. It is the authors' view that there remain significant gaps in water managers' understanding as to what aspects of the contemporary management regime require overhaul to achieve integrated management and the improved outcomes that could be expected, as compared with separate management arrangements. Such lack of understanding is an important impediment to the governance, institutional and physical infrastructure reforms whereby planned conjunctive use could improve existing management and regulatory arrangements. Reforms may also be impeded by different 'ownership' models of groundwater and surface water delivery infrastructure and the associated entitlement regime (i.e. private and/or public); a situation that has implications for social and institutional behaviour and ultimately the adoption of a conjunctive management approach.

This paper is intended to provide insight into these barriers to adoption and hence provide a new focus on an old paradigm; a focus intended to make progress with the objective of improved water management and water use efficiency and so support longer term outcomes in the form of improved food security in critical parts of the world.

Part 1: Baseline

2 Concepts and misconceptions of conjunctive use

In most climates around the world, precipitation, and consequently peak river discharge, occurs during a particular season of the year, whereas crop irrigation water requirements are at their greatest during periods of low rainfall when unregulated stream flows are significantly lower. For many irrigation systems, water supply is aligned with crop water requirements through the construction and management of dams, which capture water during periods of high flow, enabling regulated releases to meet crop water requirements. However, the construction, operation and distribution of water from dams are inherently costly undertakings that have social and ecological impacts upon communities and the environment in and on which they are built. Furthermore, dams and the associated distribution systems are commonly subject to high system losses through evaporation and leakage, though it is debateable whether the latter is actually detrimental given that it often contributes substantially to groundwater recharge.

Conversely, under natural recharge regimes, groundwater storage requires no infrastructure, the aquifer serving as the natural distribution system. The point of irrigation, in a groundwater-fed irrigation command, is commonly opportunistically located close to the groundwater extraction point, which in turn is integrated into on-farm irrigation infrastructure. Under a sustainable extraction regime, groundwater of a suitable quality can provide a reliable source of water either as a sole supply of water, or to supplement alternative sources. Commonly, the large storage to annual use ratio typical of many regional aquifers means that the reliability of supply from groundwater is less affected by seasonal conditions than are surface water systems, and may indeed provide significant buffering against droughts. However, most intensively used groundwater systems (within the context of irrigation) are located in the semi-arid parts of the world and are characterized by relatively low annual recharge. Then the ratio of annual use to long-term annual recharge becomes the predominant measure of sustainability for these systems, independent of aquifer storage. Whilst providing a large storage and natural distribution system, aquifers are, generally speaking, unable to capture a significant portion of runoff arising from large rainfall events. Aquifers therefore do not annually harvest water on a scale that justifies the construction and operation of centralized water delivery systems based on groundwater alone.

These specific characteristics of surface and groundwater resources have important implications for the optimal design and operation of irrigation systems. However, the benefits and limitations are rarely fully considered in the optimization of system design. Rather, supply design is normally focused upon one source of water, with conjunctive use often coming as an 'after thought'. Hence, infrastructure and management responses are retrofitted to existing arrangements.

'Conjunctive use', as for many such technical terms, is the subject of a range of definitions. It is defined by Foster *et al*. (2010) as a situation where "both groundwater and surface water are developed (or co-exist and can be developed) to supply a given ... irrigation canal-command – although not necessarily using both sources continuously over time nor providing each individual water user from both sources". Alternatively FAO (1995) describes it as follows: "Conjunctive use of surface water and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economical effects of each solution and to optimise the water demand/supply balance".

Considering both of these definitions, the aim of conjunctive use and management is to maximize the benefits arising from the innate characteristics of surface and groundwater water use; characteristics that, through planned integration of both water sources, provide complementary and optimal productivity and water use efficiency outcomes.

At the farm scale, conjunctive use is implemented on a day-to-day basis with 'management' characterized by low- or micro-level decisions incorporating factors such as resource availability, costs of delivery to the crop, tradability of unused allocation and water quality. Collectively, these factors contribute to minimizing costs, optimizing production and maximizing net profitability. However, at the irrigation command level, planned conjunctive water use and management aims for higher-level objectives. Planned conjunctive use is expected to optimize productivity and equity in the management of surface water and groundwater resources (World Bank 2006) and to promote economic, environmental and social sustainability.

Depending on the relative volumetric mix of the two resources, and on the manner in which associated irrigation has been historically developed, the nature of conjunctive use at any one irrigation command will be significantly different. For example, management approaches must be different where 90 percent of the available water is from one of the two resources, as compared to the situation where neither resource supplies a majority. Also subtly, groundwater can have three separate roles within a conjunctive management framework: it can be used as an alternative method to distribute water across irrigation commands; it can be used as a storage mechanism to smooth out the supply/demand balance either across seasonal patterns of water availability, or across decadal variability in climate; or it can be used to manage shallow water tables to reduce salinization and waterlogging. Management (and governance) approaches must be aware of these subtleties in attributes and plan accordingly.

Within this context, Sahuquillo (2004) discusses the use of aquifer storage and the partitioning of its use into artificial recharge *versus* the alternate use of groundwater and surface water depending on seasonally available water. Related to Sahuquillo's partitioning, an important consideration when conjunctively managing surface water and groundwater is the degree of connection between the two water resources – or the overall resource 'connectivity'. Conjunctive use refers to the way in which water resources are managed, whereas a 'connected system' refers to an environment where surface water and groundwater are effectively one connected resource. Most conjunctive use systems use the connectedness of the systems to the advantage of the user; however, natural connectedness is not a necessary feature. Engineered intervention can modify the degree of connectedness where it is desired and economically beneficial.

It is also important to note that, fundamentally, connectivity has nothing to do with conjunctive management. One is a physical attribute of the water system; the other is a form of management. However, they are related in that recognition of connectivity provides the context and framework within which conjunctive management should be planned and undertaken. When groundwater is extracted from a connected system, it may induce recharge from the surface water body, reducing the volume of available surface water. In all circumstances, however, the important consideration for management is the time lag for the effects of use of one resource to be transmitted to the other resource, regardless of how natural or engineered the connectivity. Where time lags are long, specific management challenges are evident and present major impediments. Similarly, when surface water is diverted from a connected system, it can reduce aquifer recharge and therefore the availability of suitable quality groundwater for extraction. If surface water and groundwater are managed separately in connected systems, care must be taken to avoid 'double accounting' when allocating surface water and groundwater from the one connected resource.

Whilst the aquifer provides a natural storage system to source groundwater during periods of demand, optimal management may take advantage of unutilized storage capacity through Managed Aquifer Recharge (MAR) whereby recharge is enhanced for later recovery. From a conjunctive use perspective, such a management approach enables surplus surface water to be captured (during high-flow events) and utilized at times when the dam or streamflow is depleted or when water is required for other purposes. Groundwater recharge enhancement can be done via injection down recharge wells, storage of water in infiltration basins or slowing the natural flow of surface waters to induce additional groundwater recharge (Table 1). An example of this approach is found on the Al Battinah coastal plain of eastern Oman where highly episodic *wadi* flood flows are captured by dams, and the retained water is encouraged to recharge the productive gravel aquifer underlying the area. However, in general, aquifers rarely offer large enough storage capacity for absorbing large volumes of floodwater in a short period of time (FAO, 1995).

The use of artificial recharge (or MAR) as a management option couples the attributes of the aquifer system with those of the surface water system without relying upon the natural hydrological regime of the water cycle. In effect, it decouples the need for physical connection between surface water and groundwater resources through engineering interventions. MAR as an adjunct to conjunctive management would in most cases only be likely to occur through coordinated planning which may range from village-scale low-technology water harvesting approaches, to technically sophisticated approaches (as increasingly being adopted in the developed world). Irrespective of the degree of technical sophistication, the planning requirements associated with a successful MAR initiative are such that it is unlikely to be adopted where spontaneous 'farm scale' conjunctive use prevails.

Table 1: Summary of types of aquifer recharge enhancement strategies (Foster et al. 2003)

Type	General Features	Preferred Application
Water harvesting	**Dug shafts/tanks** to which local storm runoff is led under gravity for infiltration	In villages of relatively low-density population with permeable subsoil
	Field soil/water conservation through terracing/contour ploughing/afforestation	Widely applicable but especially on sloping land in upper parts of catchments
In-channel structures	**Check/rubber dams** to detain runoff with first retaining sediment and generating clearwater	In gullies with uncertain runoff frequency and high stream slope
	Recharge dam with reservoir used for bed infiltration and generating clearwater	Upper valley with sufficient runoff and on deep water-table aquifer
	Riverbed baffling to deflect flow and increase infiltration	Wide braided rivers on piedmont plain
	Subsurface cut-off by impermeable membrane and/or puddle clay in trench to impound underflow	Only wide valleys with thin alluvium overlying impermeable bedrock
Off-channel techniques	**Artificial basins/canals** into which storm runoff is diverted with pre-basin for sediment removal	On superficial alluvial deposits of low permeability
	Land spreading by flooding of riparian land sometimes cultivated with flood-tolerant crops	On permeable alluvium, also with flood relief benefits
Injection wells	**Recharge boreholes** into permeable aquifer horizons used alternately for injection/pumping	Storage/recovery of surplus water from potable treatment plants

At the general level, the benefits attributed to optimizing conjunctive use of surface and groundwater have been investigated over many years through theoretical modelling and studies of physical systems. These benefits take the form of:

- economic gains;
- increases in productivity;
- energy savings;
- increased capacity to irrigate via larger areas;
- water resource efficiency; and
- infrastructure optimisation.

However, there are few published analyses of the actual socio-economic benefits that can be attributed to the implementation of conjunctive use management in specific irrigation commands. This is a major impediment to further communicating the positive messages regarding conjunctive use. However, an example of such studies includes Bredehoeft and Young (1983), who modelled a twofold increase in net benefit arising from conjunctive management. Another is the Agriculture and Rural Development Group, World Bank (2006), which reported a 26 percent increase in net farmer income, substantial energy savings, increased irrigation and substantial increase in irrigated crop area for Uttar Pradesh, India, as a result of conjunctive management of monsoon floodwaters in combination with a regional groundwater system.

2.1 Systems that occur spontaneously and systems that are planned

The introductory section of this paper highlights the two fundamentally different approaches to conjunctive use management, however, there is a continuum in the way that conjunctive management evolves from spontaneous (or incidental/unplanned) conjunctive use at one end, to planned conjunctive management and use at the other.

Planned conjunctive management and use of surface water and groundwater are usually practiced at the State or regional level and can optimize water allocation with respect to surface water availability and distribution, thus reducing evaporative losses in surface water storages and minimizing energy costs of irrigation in terms of kWhr/ha (Foster *et al.*, 2010). Planned conjunctive management is best implemented at the commencement of a development although experience has shown optimal outcomes may be difficult to achieve when attempts are made to redesign and retro-fit the approach, once water resource development is well advanced.

Where groundwater and surface water are used conjunctively in various parts of the world, spontaneous use prevails. Foster and Van Steenbergen (2011) emphasize that spontaneous conjunctive use of shallow aquifers in irrigation-canal-commands is driven by the capacity of groundwater to buffer the variability of surface water availability enabling:

- greater water supply security;
- securing existing crops and permitting new crop types to be established;
- better timing for irrigation, including extension of the cropping season;
- larger water yield than would generally be possible using only one source;
- reduced environmental impact; and
- avoidance of excessive surface water or groundwater depletion.

Foster *et al.* (2010) report that the most common situation in which spontaneous conjunctive use of surface water and groundwater resources occurs is where canal-based irrigation commands are:

- inadequately maintained and unable to sustain design flows throughout the system;
- poorly administered, allowing unauthorized or excessive off-takes;
- over-stretched with respect to surface water availability for dry season diversion; and
- tied to rigid canal-water delivery schedules and unable to respond to crop needs.

Additionally, spontaneous conjunctive use is also driven to a large degree by poor reliability of water quality in surface water supply cannels. Wells become an insurance against this unreliability. Poor water quality is a common factor at the tail of most irrigation canal systems and usually reflects poor infrastructure maintenance. These factors lead to inadequate irrigation services. As a consequence, the drilling of private waterwells usually proliferates, and a high reliance on groundwater often follows (Foster *et al.*, 2010).

Foster and Van Steenbergen (2011) report spontaneous conjunctive groundwater and surface water use in Indian, Pakistani, Moroccan and Argentinean irrigation-canal commands which have largely arisen due to inadequate surface-water supply to meet irrigation demand. Many other examples from developed countries also show that it is not simply a developing country problem – it is an inherent problem wherever canal-based irrigation is practiced and where there are challenges in terms of reliability of water supply and quality.

In summary, the spontaneous approach to the conjunctive use of surface and groundwater sources reflects a 'legacy of history'. The focus for green-field irrigation developments is primarily access to water, rather than the efficient and optimal use of that water; a consideration that does not gain attention until competition for water resources intensifies. Advancing beyond the farm-scale spontaneous access to each water source to a planned conjunctive management approach entails significant technical, economic, institutional and social challenges that can only be overcome with an effective governance model.

2.2 Types of aquifers

Conjunctive use can be practiced in a large number of combinations of surface water and groundwater regimes. Generally, surface water systems have high annual flow volumes and tend to be regulated, perennial rivers, whereas groundwater systems show much more variation. There is, however, a distinction between those integrated resources systems where conjunctive use has developed spontaneously and those where it is planned.

Planned conjunctive use systems can be developed on most groundwater regimes where there is adequate storage and well yield to enable efficient utilization of both the supply and demand side of the equation. The only distinction, effectively, is the degree to which the aquifer system provides a substantial natural connectivity to the surface water system, compared with those where constraints in hydrological linkages require significant engineering to overcome limitations in connectivity. Where the degree of connectivity between surface water and groundwater is poor or limited, engineered solutions can be used to transfer water from one resource to another. Within such aquifers, these inherent conditions may require MAR schemes to be adopted, sometimes on a large scale, subject to economic viability and to a range of attributes of the aquifer/source water required for feasible MAR. Such planned and engineered solutions ultimately are dependent on the level of investment available by either government or the private sector, and the productivity benefits that can be achieved.

The types of aquifers involved in conjunctive use regimes that are spontaneous in nature are usually restricted to types that exhibit certain attributes. Generally, such systems are broad regional alluvial aquifers that have good connection either with associated large rivers or with irrigation command areas, both of which have the potential to provide a significant source of recharge. Previous work has documented that the potential for conjunctive use varies considerably with the type of aquifer involved (Foster *et al.*, 2010). These types can be partitioned into four major groupings (Table 2).

This typology was further refined (Foster and van Steenbergen, 2011: Figure 1) to include variation associated with position in terms of the longitudinal profile of the alluvial system; namely, outwash and peneplain, floodplain and coastal plain. Each of these settings provides a different style of aquifer material, depth to water table and surface water-to-groundwater connectivity.

Table 2: Aquifer typology (after Foster et al., 2010)

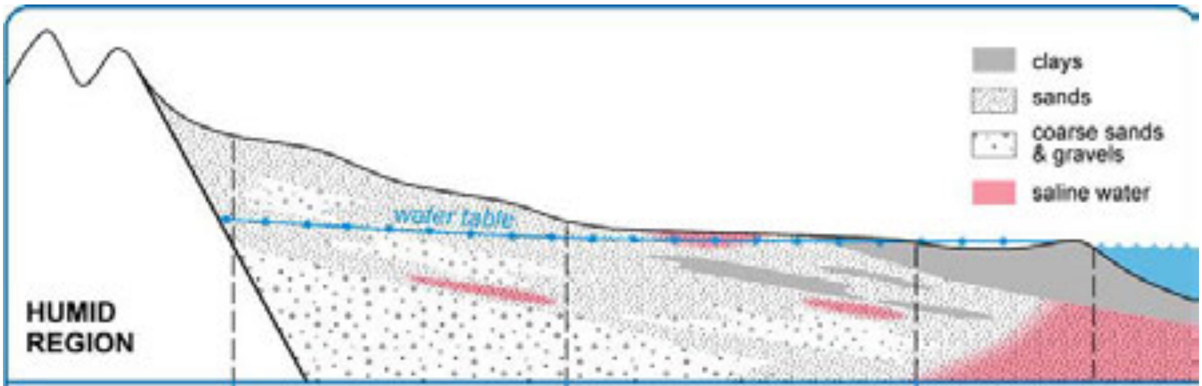
Aquifer Type	Example Location
Upstream humid or arid outwash peneplain	Indian Punjab-Indus Peneplain, Upper Oases Mendoza – Argentina Yaqui Valley, Sonora – Mexico
Humid but drought-prone middle alluvial plain	Middle Gangetic Plain – India Middle Chao Phyra Basin – Thailand
Hyper-arid middle alluvial plain	Middle Indus Plain – Pakistan Lower Ica Valley – Peru Tadla – Morocco Tihama – Yemen
Downstream alluvial plain or delta with confined groundwater	Ganges Delta – Bangladesh Lower Oasis Mendoza – Argentina Nile Delta – Egypt

Clearly, there are some minimum requirements that will act as a threshold for groundwater to be seriously considered as part of a conjunctive use system. These requirements relate to the aquifer attributes that control the size of the resource, the rate at which it can yield groundwater and the economic viability of extraction. This means that aquifer size (storage ability), aquifer or basin effective hydraulic conductivity and the depth to the water table/potentiometric surface are critical. So too is water quality.

2.3 Highly *versus* poorly connected systems

When groundwater and surface water are hydrologically connected, the interchange of the resource between the systems requires consideration during the management process. Accordingly, it is an aspect that must be considered within a conjunctive use framework, as it can shape the available options and hence define the optimal approach to conjunctive management.

Connectivity comprises two important components: the degree of connection between the two resources and the time lag for extraction from one resource to impact upon the other. A highly connected resource would be one where the degree of connection is high and the time lag for transmission of impacts is very fast. A fundamental tenet of connectivity understanding is that, essentially, all surface water and groundwater



ALLUVIAL SETTING	OUTWASH & PENE-PLAIN	FLOOD PLAIN	COASTAL PLAIN
Hydrogeological Conditions	unconfined high-yielding aquifer with increasingly deep water table but rapid vertical recharge	multi-layered aquifer with shallow water table and moderate waterwell yields but with some 'rejected recharge'	confined aquifer with very restricted vertical recharge and reducing effective thickness
Water Resource Management Implications as in Humid Regions	much care needed to avoid 'double-accounting' due to infiltration of surface water via irrigation systems	poorly-managed surface water irrigation results in soil water-logging/ salinisation; river baseflows used for irrigation can be greatly reduced by 'upstream' consumptive groundwater irrigation use	aquifer highly vulnerable to saline water intrusion on intensive exploitation and reversal of natural hydraulic gradients
Water Resource Management Implications as in Hyper-Arid Regions	high soil-profile salinity under natural vegetation mobilised when irrigated cultivation introduced	groundwater at depth naturally saline with freshwater restricted to lenses beneath major rivers/irrigation systems	surficial aquitard may also contain saline water which can seep downward

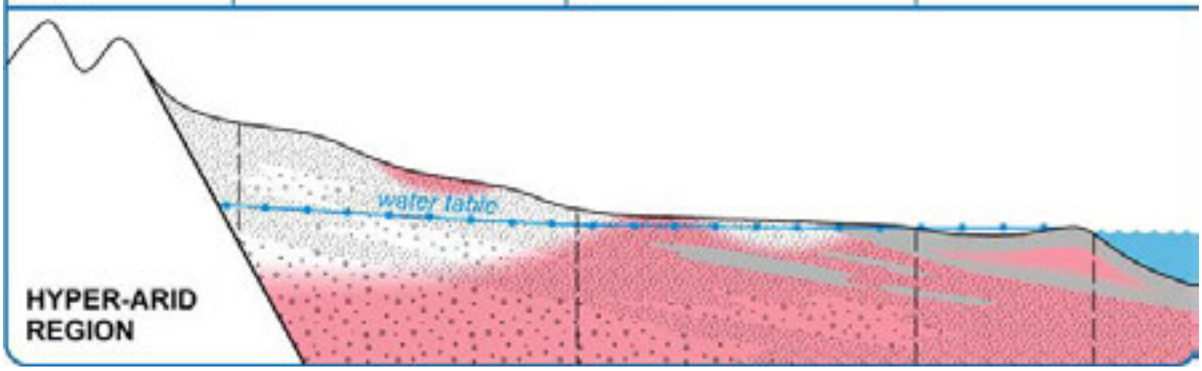


Figure 1: Schematic long-profile of a typical alluvial groundwater system in a humid region detailing the variation in groundwater-surface water connectivity and salinization hazards (from Foster et al., 2011).

systems are connected and that it is just a matter of time for impacts to be felt across the connection. Important exceptions to these truisms are that of canal-dominated irrigation commands, where the water table is below the water level in the canal system or where the water table is shallow and groundwater extraction is capturing losses to evapotranspiration. In such areas recharge may also be dominated by irrigation-induced rootzone drainage, and hence vertical unsaturated zone processes may control the interaction/connectivity process. In these latter areas, the canal distribution systems may provide a significantly reduced contribution to groundwater extraction.

A large body of research and investigation has been undertaken on the issue of connectivity and this will not be dealt with in any detail here. The salient issue for conjunctive management, especially in a planned environment, is to understand the nature of connectivity as a factor in resource use optimization and to ensure that connectivity is understood when considering water resource accounting in a conjunctively managed water system.

Figure 2 provides examples of connected gaining and losing streams and of streams that fluctuate between these two situations (a, b and d respectively). It also indicates that the head difference between the river and the aquifer determines the direction of flow. The rate of flow between the river and aquifer will depend on the hydraulic conductivity of the aquifer and the hydraulic conductance of the bed of the river. Figure 2 (c) provides an example of a stream that is connected to the adjoining aquifer through an unsaturated zone; this situation is usually found in arid areas. The interchange of water between surface water and groundwater is controlled by the hydraulic conductivity of the unsaturated zone (SKM, 2011).

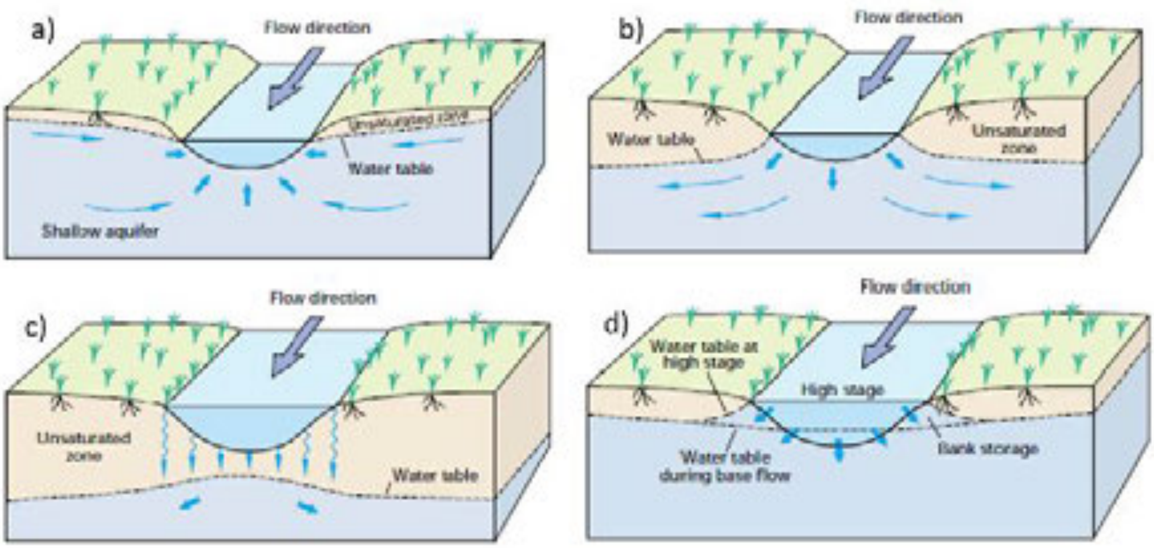


Figure 2: Connectivity relationships: a) gaining connected system; b) losing connected system; c) disconnected system; d) fluctuating connected / disconnected system (modified after Winter et al., 1998).

The timing of the impacts is very important. Bredehoeft (2011) has shown that timing is important to water resources managers whether the impacts from groundwater pumping on a stream occur within an irrigation season, or over a longer period. Connectivity will control the timing for groundwater recharge and the timing of changes in discharge from groundwater to the streams due to groundwater abstraction.

Figure 3 shows a simple example of the relationship between groundwater pumping and the timing of impacts felt in a connected surface-water system. In this hypothetical example, the full impact time (t_{100}) has not been specified, but it can vary from very short (days) to very long (many decades). It is important to attempt to understand or calculate the likely t_{100} time so impacts can be accounted for within integrated water resource plans.

Within connected systems, groundwater abstraction will therefore induce aquifer recharge from the surface water body reducing the volume of available surface water, although as shown in Figure 3, the magnitude of the impacts will be a function of time, which in turn will be dependent upon the properties of the associated hydrology. Similarly, when surface water is diverted from a connected system it can reduce aquifer recharge and therefore the availability of suitable quality groundwater for extraction. If surface water and groundwater are managed separately in connected systems, care must be taken to avoid 'double accounting' where the same volume of water is potentially attributed to both the surface and groundwater resource. The issue of double accounting is explored in more detail elsewhere in this paper (Box 1), but it is worth noting within this section that it is generally reflected in situations where streamflow leakage is accounted both as streamflow and as groundwater recharge. Similarly, baseflow can be accounted both as groundwater discharge and as normal streamflow.

In cases where the two water resources are highly connected with short time lags, conjunctive management may be supported by a transparent water-accounting framework that can be reported on for both surface and groundwater on an annual basis. It may provide flexibility in the way in which surface and groundwater is allocated on an annual basis, and could facilitate the development of a robust two-way water-trading regime

Box 1. How to avoid double accounting

As previously discussed in this paper, 'double accounting' relates to the dual allocation of a single parcel of water. It is a common occurrence throughout the world due to the evolution of water resource development and associated regulatory arrangements, and it may reflect an absence of a proper water resource assessment, poor understanding of the water balance, or the undertaking of independent resource assessments for surface water and groundwater. Two common situations occur.

Firstly, when surface-water-based irrigation causes recharge to the groundwater system. The groundwater recharge is seen as a 'loss' from a surface-water point of view. A typical water resource management response may be to invest in improved sealing canals or constructing pipelines, however this may not be the most efficient response. In situations where groundwater recovery is financially viable, a more efficient approach may be to utilize aquifer storage capacity and the diffuse distribution of the resource provided by the groundwater system. If in such situations, canal leakage has already been allocated to surface water users, then it should not also be allocated to groundwater users. Instead, mechanisms such as trade should be used to transfer entitlements from one user to another, and hence maintain the integrity of the water accounting framework. Furthermore, any decision to reduce leakage through canal lining, and hence reduce recharge, would require revision to the water resource assessment and may require appropriate adjustments to entitlements, particularly if such recharge had been allocated to groundwater users.

Secondly, the classical surface water/groundwater interaction situation is where groundwater discharges to become base flow. Considered in isolation, this may be deemed as a "loss" from a groundwater management perspective and a justifiable basis for allowing groundwater pumping to substantially reduce stream flow. Similarly from a surface-water management perspective, the significance of groundwater discharge in maintaining stream flow during the dry season may be poorly recognized. There are many examples in the literature (for example, Evans, 2007) where the implications of not recognizing such interaction have contributed to the depletion of rivers around the world. The assessment of the interaction requires an integrated resource assessment, with the water balance taking into account all extraction regimes and the consequential impacts on both groundwater and surface water resources.

Eliminating double accounting requires integrating water entitlements with a water balance that reflects the full hydrological cycle, and hence fully appreciating the amount and timing of the interaction between groundwater and surface water. It is also critical to appreciate the temporal variability of the process. In this case, it is important that the conjunctive planning time frame be long term, for example 50 years. Short-term planning to meet political or social objectives will not achieve effective conjunctive management. There are some relatively rare situations where there is effectively no interaction between groundwater and surface water. In such situations, conjunctive management is relatively less complicated, but nonetheless important in terms of achieving optimal water management outcomes.

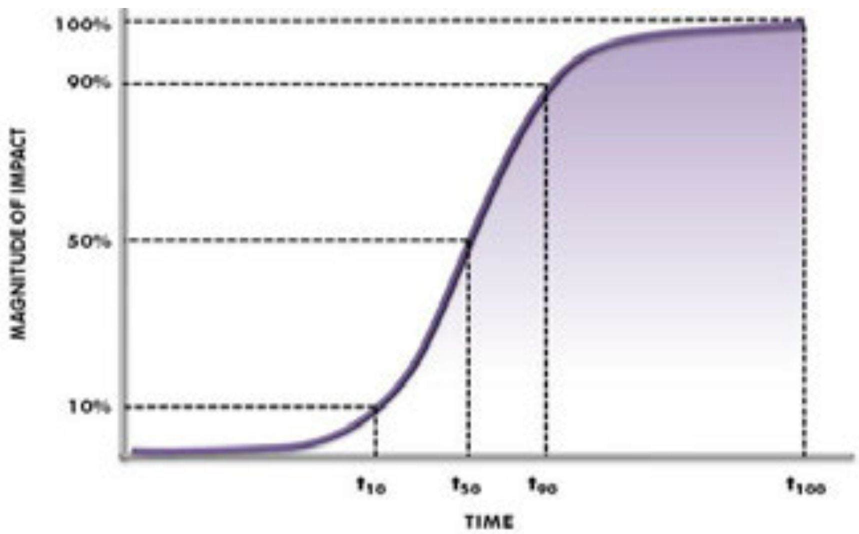


Figure 3: Simplified groundwater pumping time and impact relationship.

between the groundwater and surface water system, providing third-party impacts are understood and effectively managed.

Conjunctive management within an environment where surface and groundwater systems are poorly connected is unlikely to provide such a degree of integration. Whilst there are opportunities for integration (such as the application of MAR discussed previously) and for taking advantage of the unique attributes of groundwater and surface water, such as storage, distribution and reliability in dry periods (also identified earlier), the opportunities and benefits that have the potential to arise from conjunctive use will be different, reflecting differences in the hydrological environment. In other words, within poorly connected systems, conjunctive management will be framed around the task of complementary and integrated management of water use, without the need for such integration to consider hydrological linkages of the water sources. This is modified, however, where engineered solutions enable better (anthropogenic) connection between the two parts of the water system.

2.4 Salinity control as a driver

Major benefits and contributing drivers to the establishment of conjunctive use in irrigation commands are water-table control and ensuing soil-salinity management. As has been shown throughout India and Pakistan, groundwater extraction from unconfined aquifers supports the management of soil salinity by providing an opportunity for leaching of accumulated salts. In these cases, the factors discussed above that drive development of the groundwater system (primarily hydraulic conductivity) are not as important as the benefits of sub-surface drainage. It is important that governance arrangements clearly acknowledge these benefits, where applicable, and that planning also considers the management of salt where abstracted water supplies are integrated into the supply system.

2.5 Technical and management differences between surface water and groundwater

The characteristics of the two primary water sources associated with conjunctive use and management (i.e. groundwater compared with surface water) are inherently different; differences that must be appreciated when optimizing their use. A summary of typical characteristics associated with groundwater and surface water resources is provided in Table 3.

Table 3: Typical characteristics of groundwater and surface water

Characteristic	Groundwater	Surface Water
Response time	Slow	Quick
Time lag	Long	Short
Size of storage	Large	Small
Security of supply	High	Low
Water quality	Poor	Good*
Spatial management scale	Diffuse	Linear
Ownership	Private	Public
Flexibility of supply	Very flexible	Not flexible

*Whilst surface water supplied within irrigation areas is generally of a higher quality than groundwater, it is worth noting that surface water quality often deteriorates toward the downstream end of the distribution system if the irrigation delivery system receives drainage return flows. This applies particularly in areas where drainage systems are subject to saline groundwater inflows.

Given the extent and diversity of irrigation systems covering a vast range of physical environments throughout the world, there are many situations where the characteristics of the surface/groundwater components of local water resources are represented by the 'typical' characteristics presented above. Nonetheless, physical differences and differences in the history of development of the two resource types provide both challenges and benefits to conjunctive management and use. To make progress on conjunctive management, the specific characteristics of groundwater and surface water in the target region must be assessed. Such an assessment includes the social, economic and environmental aspects (the so-called 'triple bottom line') so as to evaluate how the particular characteristics of the hydrological environment can be integrated to achieve optimum outcomes.

It is almost mandatory in current times to ensure that water resources management is undertaken not only in an integrated manner, but also cognisant of triple-bottom-line issues.

2.6 Overview of major irrigation systems throughout the world where both surface water and groundwater are used

Generally, conjunctive use, especially in the spontaneous form, has developed on the major alluvial plains and their associated aquifers of the world (as discussed above). Foster *et al.* (2010) contend that the above-mentioned settings, together with variations of average rainfall and geomorphological position, control the potential for conjunctive use for irrigated agriculture. A further driver appears to be water availability, or more pertinently, water scarcity – the pressure to find and utilize other water sources increases as water becomes scarce. Nevertheless, the scale of the adoption of conjunctive use is generally controlled by the scale of the groundwater system.

Historically, surface water has been the primary source in the majority of such systems, with groundwater providing an alternative source when surface water availability is low, particularly during periods of drought. However, with increasing demand for water, the value of groundwater is achieving greater recognition, becoming in many areas an important primary source of water supply for irrigation. The increased value for groundwater more generally has been driven by growth in irrigated areas that were traditionally supplied from surface water, hence increasing the demand from these historic sources.

The use of groundwater for irrigation has generally increased worldwide (in some cases exponentially) since the 1950s. For instance, surface water withdrawals accounted for 77 percent of all irrigation in the United Kingdom (UK) in 1950 but, with increasing groundwater development, withdrawals declined to just 59 percent by 2005 (USGS, 2011). Similar patterns are apparent in the developing world, although surface water canal commands generally remain at the heart of irrigated agricultural districts, with groundwater being used mainly in times of surface water shortage.

There are a number of different factors influencing increased groundwater extraction with the dominant drivers being a function of local circumstance. Some of these important drivers are presented in Table 4. Also included in this table are factors that have contributed to users maintaining surface water as their sole source of supply.

Table 4: Summary of drivers for sole use of groundwater or surface water resources

Drivers of Resource Use	Groundwater Resource	Surface Water Resource
Variable climate	A highly variable climate will typically favour users of groundwater resources, as groundwater characteristically provides a higher reliability of supply than surface water.	
Poor surface water quality	Poor surface water quality (often generated by the irrigation system itself) will favour groundwater use.	
Poor groundwater quality		Surface water will remain the dominant resource when groundwater quality is poor.
Lack of adequate infrastructure	Gaps or failures in infrastructure (or in its operation and maintenance) that delivers surface water to users will favour groundwater use.	
Depth of groundwater resource		Groundwater resources found at significant depths below the surface will incur significant pumping costs and hence often favour the use of surface water resources.

Drivers of Resource Use	Groundwater Resource	Surface Water Resource
Traditional farming practices	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices.	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices.
Discovery of a new groundwater resource	The discovery of a new groundwater resource will drive groundwater use; particularly in well-developed systems where surface water allocations have been capped. It is especially so if there are fewer regulations on groundwater use.	
Economic value associated with production	Where economic return is significant, investment into obtaining additional water from a groundwater resource is more likely to occur.	If the economics in terms of farm income are distorted towards surface water use, farmers will be reluctant to incur additional cost to change water sources or use.
Energy pricing	Subsidized energy costs of pumping can encourage groundwater use	
Technology advances	Advances such as managed aquifer recharge mean that utilization of groundwater resources is often more feasible due to an increase in the volume of available water and security of supply. Also advances in pumping technology can encourage groundwater usage.	
Irrigator education and understanding	A lack of irrigator education and understanding of the benefits of conjunctive groundwater and surface water use can inhibit deviation from groundwater supply as a sole resource.	A lack of irrigator education and understanding of the benefits of conjunctive groundwater and surface water use can inhibit deviation from surface water supply as a sole resource.
Institutional structures	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use, surface water or groundwater (whichever is currently favoured) will remain the primary water source for users.	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use, surface water or groundwater (whichever is currently favoured) will remain the primary water source for users.
Shallow water-table mitigation	Large volumes of irrigation recharge can lead to artificially high water-table levels, which threaten surface and groundwater quality and the environment itself. Government incentives that encourage groundwater use as a mitigation measure ultimately drive groundwater use.	

In surface-water irrigation commands, there can be differences in water security based on how close the particular farm off-take is to the primary diversion canal, especially where the delivery infrastructure is operated (or performs) in an inefficient manner. Those close to the primary source (termed the 'head' of the irrigation command) are likely to benefit from regular supplies whereas those at the end of the delivery system (the 'tail') are subject to the efficiency of the delivery canals and the compliance of other farmers to access rules. In some cases the quality of the delivered water will deteriorate as the delivery system also sources groundwater discharge from irrigation-induced shallow water tables. In such cases, individual wells become an insurance policy against both diminished and uncertain supply and poor water quality.

2.7 Lessons learnt about governance

This paper is essentially about the governance approaches that are required to implement conjunctive use management in irrigation commands. Groundwater governance is defined here as the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision-making between and among different jurisdictional levels – one of which may be global (adapted from Meganck and Saunier, 2007).

There are different implications for governance arrangements depending whether one is retrofitting planned conjunctive use to an existing irrigation command, or whether conjunctive use is being developed in a 'greenfields' situation. These implications will be further developed in a following section, but it is useful to summarize the commonality of current approaches and lessons learnt at this point.

In both cases, the following will be required:

- institutional strengthening to ensure that integrated water management occurs, together with explicit decisions about system management and operation[1];
- commitment to sustainability objectives that target environmental, social and economic outcomes;
- decisions about future investment in infrastructure and cost recovery;
- strong policy and legislative leadership to drive a planned approach, within a compliance culture;
- clear and robust implementation and delivery mechanisms to ensure the central planning and policy approach can be taken through to on-ground action;
- participatory involvement by the grass-roots water users and related stakeholders; and
- technical knowledge of the surface water and groundwater systems to enable efficient use of both resources, as well as capacity building to apply this technical knowledge.

However, irrigation commands where spontaneous conjunctive use has evolved over time will also require a significant investment in planning to enable integration of opportunistic pumping within the optimal conjunctive use framework. This will require (in addition to the above):

- establishment of institutions that provide complementary planning and regulatory functions;
- modification of current behaviour, that may be achieved through –
    - implementation of a compliance management framework;
    - potential use of either market instruments or direct incentives to encourage and effect farmer change; and
    - targeted extension programmes that, through education and demonstrations, enable farmers to realize the on-farm benefits to be provided by the planned approach.

Because spontaneous conjunctive use has usually evolved over time, policy objectives such as sustainability may not be fully evident or understood, unless serious resource depletion is already placing physical constraints on access. Regulated reductions in access may therefore create tensions, highlighting the value in improved understanding by irrigators, and the value in stakeholder involvement within the planning process.

[1] Institutionally, international experience is that surface water management is almost always separated from groundwater management, though they may share the same 'head' institution or governing authority. It is the authors' view that major institutional reform is required to bridge this 'divide' not just in name but through planning behaviours and operational arrangements.

Where conjunctive use has grown up spontaneously around a previously surface-water-dominated irrigation command, one might expect management to be somewhat centralized and rigid. Where it has grown around a strongly groundwater-dominant irrigation command, management approaches may be less rigid and more informal, to the point where there is little regulatory control. Each of these end members will represent particular challenges in achieving a governance model that is able to support a technically robust and appropriately designed conjunctive management model.

Part 2: Diagnostic

3 Examples of successes and failures of conjunctive use

The following sections describe some examples of irrigation commands where conjunctive use of groundwater and surface water resources occur. This chapter draws heavily on the work of GW-MATE (see Foster *et al.*, 2010 and related references) and is by no means exhaustive. Examples are provided as a way of describing the breadth of types of conjunctive use systems currently operating worldwide. It is acknowledged that conjunctive use of groundwater and surface water already occurs in most countries where irrigated agriculture is practiced, in the developed and developing world. However it is also recognized that, whilst conjunctive use is probably the norm more so than the exception, its operation within an integrated water management framework is where adoption is significantly lacking.

It is rare for institutions or commentators to document the failures of conjunctive use management, therefore the following examples focus entirely on successes. However, the lack of documentation of failures is in itself a major impediment to this diagnosis and to the development of improved management of conjunctive use of surface water and groundwater.

3.1 Uttar Pradesh – INDIA

Foster *et al.* (2010) have described the setting for conjunctive use in the State of Uttar Pradesh in India, which is categorized as a humid but drought-prone middle-alluvial-plain hydrogeological setting (Table 2 above). The alluvial plains of the Ganges Valley (the Indo-Gangetic Plain) in Uttar Pradesh are underlain by an extensive aquifer system holding groundwater that represents as much as 70 percent of the overall irrigation-water supply. This is one of the largest groundwater storage reserves in the world. Its utilization as a water resource has primarily arisen in response to reduction in supply and unreliable operation of the irrigation canal systems. The aquifers are directly recharged from infiltrating monsoon rainfall but also indirectly from canal leakage and poor applied irrigation efficiency (i.e. excess rates of field application) – a common scenario in such hydrogeological settings.
Increasing groundwater abstraction has resulted in a declining water table, particularly in high intensity ‘groundwater exploitation zones’, whereas in other areas (in some cases within 10-20 km), flood irrigation and canal leakage have maintained shallow water tables. The decline in water tables in some areas is correlated with evidence of irrigation tubewell dewatering, yield reduction and pump failure, together with hand-pump failure in rural water-supply wells. Conversely, threats arising from shallow water tables elsewhere are evident in around 20 percent of the land area being subject to shallow or rising groundwater levels, with soil water-logging and salinization leading to crop losses and even land abandonment (Foster *et al.*, 2010).

Protocols for the operation of the distributary canal system exist, but they have not been strictly adhered to in the past, and this has contributed to an imbalance in surface-water delivery through the system.

In the light of the challenges posed by rising water tables in some areas and declines in the water resources elsewhere, in the Jaunpur Branch canal-command area in Central Pradesh a ‘more planned conjunctive-use approach’ is being implemented. The adopted approach uses extensive datasets and associated analysis to understand the hydrogeological, agronomic and socioeconomic situation. Strategies include: attempts to reduce leakage through maintenance of bank sealing in major irrigation canals, enforcing current operational codes, promotion of tubewell use in non-command and high-water-table areas, and investment into research and specialist extension in soil salinity mitigation and sodic land reclamation.

These activities are being aligned with the pursuit of an appropriate management plan, for which the land surface has been subdivided on the basis of hydrogeologic and agroeconomic criteria into ‘micro-planning and management zones’. For each zone a canal reach (e.g. head, mid or tail) is assigned with an indication of current irrigation canal flow and water-table level. The irrigation water service situation, the groundwater resource status and the groundwater management needs are then identified.

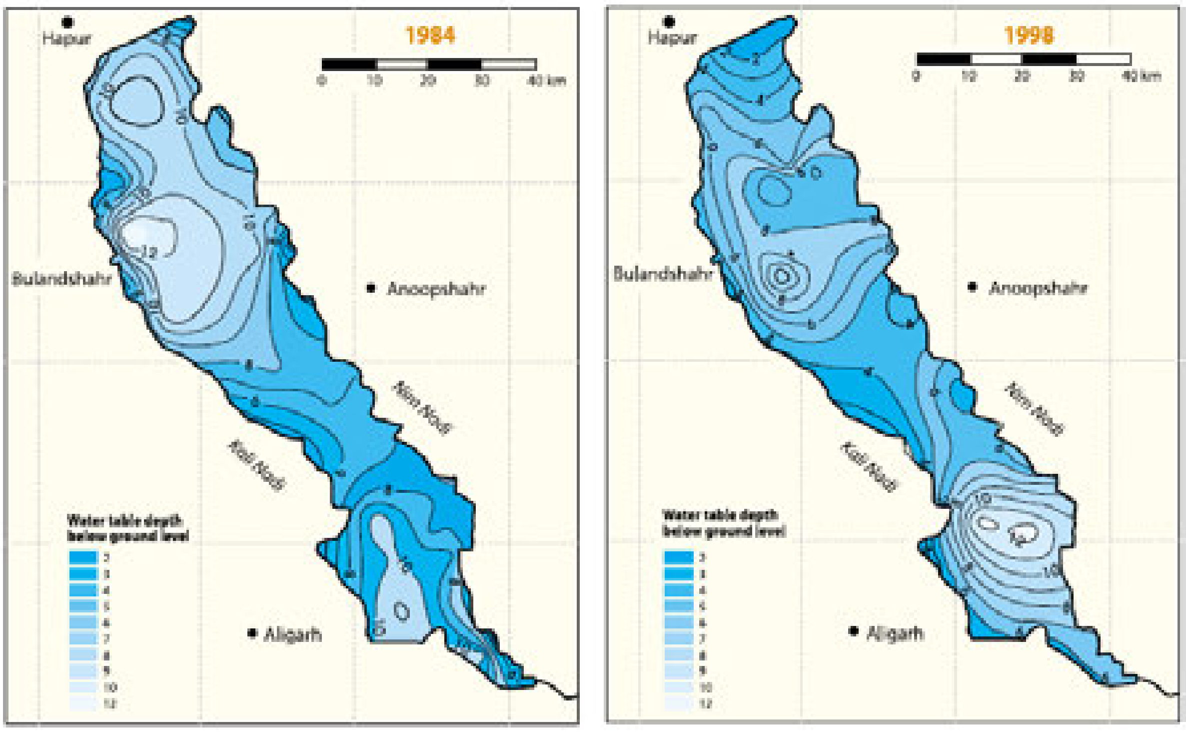


Figure 4: Comparison of water-table depth before (1984) and after (1998) recharge, Uttar Pradesh (from IWMI, 2002). Maps of the Lakhaoti Branch Canal, Utter Pradesh, India, showing post monsoon depth to groundwater before and after recharge management began. *Dark blue areas show where groundwater levels are close to the surface.*

This zoning approach allows targeted management actions that range from encouragement of groundwater use in the head end of the irrigation systems where shallow groundwater levels prevail, focusing upon higher value crops, in some areas, and on improving canal-water availability for those at the lower ends of the system. Collectively, these mechanisms are intended to provide a more balanced approach across the canal command (and beyond) and contribute to a sustainable future for agriculture in the region (Foster *et al.*, 2010). Figure 4 above shows the beneficial changes in water-table depth for one such targeted area.

IWMI (2002) describes the situation for the western Indo-Gangetic plain, where, although rainfall ranges between 650 and 1 000 mm annually, only 200 mm naturally percolate through soil layers to recharge underlying aquifers. In this area, like many others in India, groundwater pumping by farmers exceeds recharge (from rainfall and leakage from surface waters – canals and rivers – and application excess). Farmers are at the mercy of monsoon rains, which can fail to provide water when and where it is needed. The high concentration of rainfall, over a 3-month period, means the majority of water runs off the already saturated soil. During the dry season, a lack of canal water means a reliance on pumping from groundwater stores, which are not totally replenished from the previous year, hence further depletion (mining) of the aquifer system.

A 10-year pilot project (the Madhya Ganga Canal Project) undertaken in this area has demonstrated a low-cost way of using the excess surface water during monsoon season by conserving and rejuvenating falling groundwater reserves. The project involved diversion of 234 m^3/s of monsoon waters in the River Ganga to the Madhya Ganga Canal, which feeds both the Upper Ganga Canal system and the Lakhaoti Branch Canal system. Through systems of unlined (unsealed) earthen canals, water is delivered to farmers for irrigation of water-intensive monsoon crop such as paddy rice and sugarcane. The unlined nature of the canal systems and infiltration of excess irrigated water facilitates the recharge of underlying aquifers, in which the water table was raised from an average 12 m bgl to an average 6.5 m bgl. Simulations showed that, without such a conjunctive management approach, levels would have continued to decline to an average depth of 18.5 m bgl over the course of the study.

The conjunctive management of surface water and groundwater has proved productive in terms of the average net income increasing by 26 percent through reductions in pumping costs and improved cropping systems. It has demonstrated a more sustainable system through improved cropping patterns and through more reliable and sometimes new sources of water for irrigation and other uses, such as domestic/industrial supplies (e.g. providing water in previously existing dry pockets). During the dry season, drawdown from groundwater pumping prevents waterlogging and maximizes storage space for recharge during the following year's monsoon.

Unused (often lined) drainage canals constructed in the 1950s to control water logging and floods are also being targeted as a means for diverting monsoon waters across India, either for irrigation, storage and later use or for recharge to underlying aquifers. Modification of previously lined canals can aid their transformation into temporary reservoirs, where 'check structures' at suitable intervals slow down water flow and increase the aquifer recharge capacity of the carrier (Khepar *et al.*, 2000 in IWMI, 2002). In combination with the use of earthen irrigation canals, the use of old drainage networks can maximize water use and storage for very low cost compared to building new infrastructure such as dams (Khepar *et al.*, 2000 in IWMI, 2002).

3.2 Mendoza – ARGENTINA

Foster and Garduño (2006) describe the situation in the Mendoza Aquifers of Argentina, which are also highly developed within and outside existing irrigation-canal commands. The Mendoza Aquifers are characterized by an upstream arid-outwash-peneplain hydrogeological setting (Table 2 above) and are shown diagrammatically in Figure 5. The aquifers are recharged directly from the Mendoza and Tununyan rivers as they emerge from the Andean mountain chain and indirectly from irrigation canals and irrigated fields.

The General Department for Irrigation (*Departamento General de Irrigación* – DGI) is the autonomous water resource authority responsible for water management in the entire province, down to the primary canals and the delivery of water to Water Users' Associations (WUAs). Groundwater abstraction is the main source of water for irrigation outside the command of main canals and is used to supplement surface water during times of critical plant demand and in years of low flow.

The DGI's initial approach to groundwater resource management involved:

- encouraging irrigation waterwell drilling in areas outside and on the margins of existing irrigation-canal commands; and
- permitting waterwell drilling within surface-water irrigation commands, if existing canal allocation did not provide a reliable supply at times of low riverflow and/or maximum plant demand.

Although the strategy was generally a success, problems with high and increasing groundwater salinity in two areas of intensive groundwater irrigation started to emerge. Salinity distribution during 2003-2004 suggested the current groundwater flow, irrigation use and return flow were significant contributors to these problems.

In the Carrizal Valley, the expansion of high-intensity groundwater use for irrigation of export-quality viticulture and fruit production, while efficient due to application of modern irrigation practices, has put pressure on the groundwater system. Six to seven hundred active production wells were reported in the valley in 2006, with consistently elevated electricity consumption reflecting the high dependence on the wells for agricultural irrigation.

In the Montecaseros zone, the second problematic area, the aquifer system has marked layering into sub-aquifer units separated by aquitards. Groundwater salinity in the shallowest of these increased substantially between the 1970s and 1995, instigating a shift to extraction targeting deeper sub-aquifers. However, there has been downward migration of saline groundwater, thought to be related, among other things, to pumping from sub-aquifers the water of which is potentially derived from overlying strata, and less so from poorly constructed and/or highly corroded wells providing conduits for brackish water.

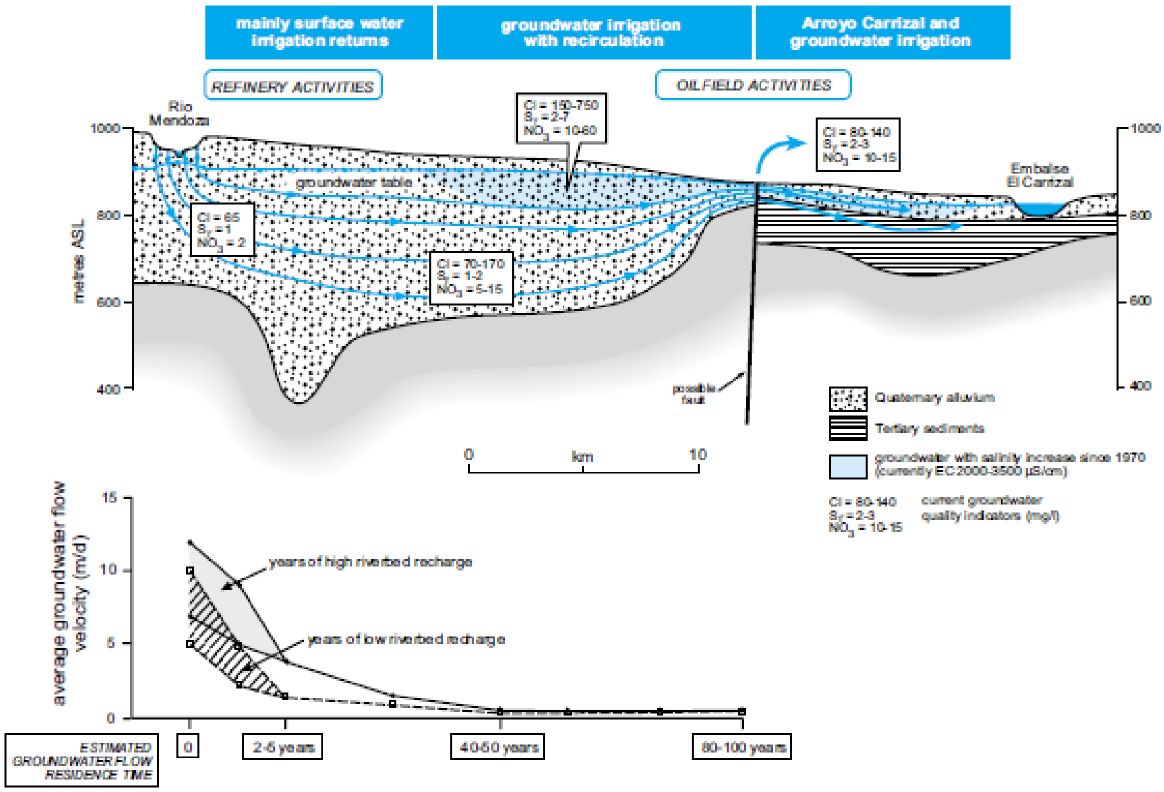


Figure 5: Hydrogeological profile along the flow direction of the Carrizal aquifer system (from Foster and Garduño, 2006).

When estimated demand exceeded available resources – following continued below-average riverbed recharge amidst concerns around falling water tables, increasing groundwater salinity in some areas, competition amongst groundwater users and between others dependent on downstream groundwater discharge –, the Carrizal Valley and Montecaseros zone were declared groundwater use restriction zones (GRZ) in 1997 and 1995, respectively.

GRZs have more rigorous waterwell-drilling controls aiming to reduce current, and prevent further, growth of groundwater abstraction. This is while still allowing: construction of more energy-efficient (replacement) wells and reallocation of groundwater resources to high-value uses by purchase and sealing of existing wells with construction of new wells at close-by locations within the same zone, even though water trading is not permitted under provincial water law. 'Sale' of excess surface water is also permitted in GRZs but with the relatively high costs of irrigation modernization, this is unlikely to be a great incentive to invest in water-saving measures.

The DGI is working towards a proactive groundwater management and protection programme to widen the base of stakeholder participation and foster shared appreciation of problems. The initial step identified to this end was to improve scientific understanding of aquifer behaviour. This has involved significant field work (e.g. intensification of groundwater level and salinity monitoring) to improve understanding of the hydrogeological structure and irrigation well abstraction/use patterns that will inform numerical modelling. Simulating various scenarios should allow evaluation of potential impacts, thus providing an improved basis for future conjunctive water use management.
Other land and water management measures to improve water-use efficiency and minimize the further mobilization of salinity instigated by DGI include:

- delivering surface water by lined canals/pipeline to increase efficiency, and reduce infiltration to uppermost saline aquifer to avoid water-table rise and increased downward leakage (Montecasero zone);
- providing additional water, from the surface water supply, to salinity affected areas by diverting excess riverflows;
- introducing drip irrigation techniques;

- backfilling or effectively sealing all disused, poorly-constructed and/or highly corroded waterwells (particularly to avoid transfer of brackish water in the Montecaseros);
- reducing rural electrical energy subsidies;
- policing and reducing illegal pumping;
- increasing riverbed recharge through works in the Mendoza riverbed; and
- providing canal water to groundwater-only areas.

These measures have had varying impacts on the water balance of the Carrizal Aquifer, which are yet to be fully realized. Some remaining challenges include the following:

- Groundwater rights have been granted in perpetuity and there is no mechanism to reduce entitlements to support more efficient use of water.
- There is an absence of legal powers and market mechanisms that would enable the transfer of surface water entitlements to areas without access rights.
- Surface water and groundwater have differential cost structures that apply to users, as groundwater users fully finance the associated infrastructure whereas surface water infrastructure has been either wholly or partly subsidized by the State.
- Local water-user groups have been focused upon surface water issues, and there has been a reluctance to engage in groundwater management issues, which would require reorganization to better reflect the distribution of users[2].

Notwithstanding the above, the Carrizal Valley strategy appeared to be succeeding according to post-2007 monitoring data that suggest partial water-table recovery and groundwater salinity reduction.

3.3 Queensland – AUSTRALIA

Hafi (2002) highlighted the importance of taking a multiple-water-resource-system perspective in addressing issues of conjunctive use of groundwater and surface water in the Burdekin delta area, Queensland, Australia (Figure 6). Within this system, there is significant interaction between surface water and groundwater resources, and hence complementary policies have been formulated for surface water and groundwater management.

The Burdekin delta is a major sugar production district in Australia and overlies a shallow groundwater aquifer, which is hydrogeologically linked to environmentally sensitive wetlands, waterways, estuaries and to the Great Barrier Reef. In addition to irrigation supply, the aquifer also supplies potable water for three towns in the delta. The Burdekin River Delta aquifer consists of sedimentary deposits, up to 100 m below the surface. An important feature of the delta aquifer is that the sediments are not continuous laterally even over short distances. Discontinuity in impervious clay layers exposes the aquifer to infiltration of water from the surface and as a result the aquifer is generally considered unconfined. In terms of the hydrogeological settings defined in Table 2 above, the Burdekin falls into the downstream alluvial delta category.

In the delta, surface water is pumped from the Burdekin River and diverted into canals to deliver to recharge pits and channel-intrusion areas and to irrigation farms (Figure 6). The channel system also delivers water to natural waterways, gullies and lagoons. The aquifer and the extensive canal, gully and lagoon system are collectively used as low-cost storage of diverted water and to capture a significant portion of the area’s rainfall runoff. When the water diverted from the river is too turbid to be used in recharge pits or in excess of recharge capacities, it is made available as a supplementary irrigation supply. In normal years, rainfall recharge from outcrop areas and discharges from flooded rivers are sufficient to recharge the aquifer. However, after several successive years of drought, the aquifer has been depleted to near sea level mainly due to pumping for irrigation and continuous discharge to the sea.

A numerical model was used to identify optimal strategies to conjunctively manage groundwater and surface water resources to maximize their economic value. The model provided solutions relating to the optimal groundwater pumping levels required to manage the groundwater resource, such that the water table does not

[2] Overcoming this issue is exacerbated by the absence of a revenue base and the politicization of the user groups towards maintaining subsidized surface-water supplies.

rise to levels that might cause waterlogging in some areas, and does not fall to a level that would permit seawater intrusion. This decision support tool has proved to be invaluable to water managers in the Burdekin River Delta. It provides information on optimal pumping quotas and the allocation of surface water resources. It further provides a basis for sustainable resource allocation, enabling decisions on the immediate use of supplies to meet short-term demand, and decisions supporting aquifer recharge for storage and future use.

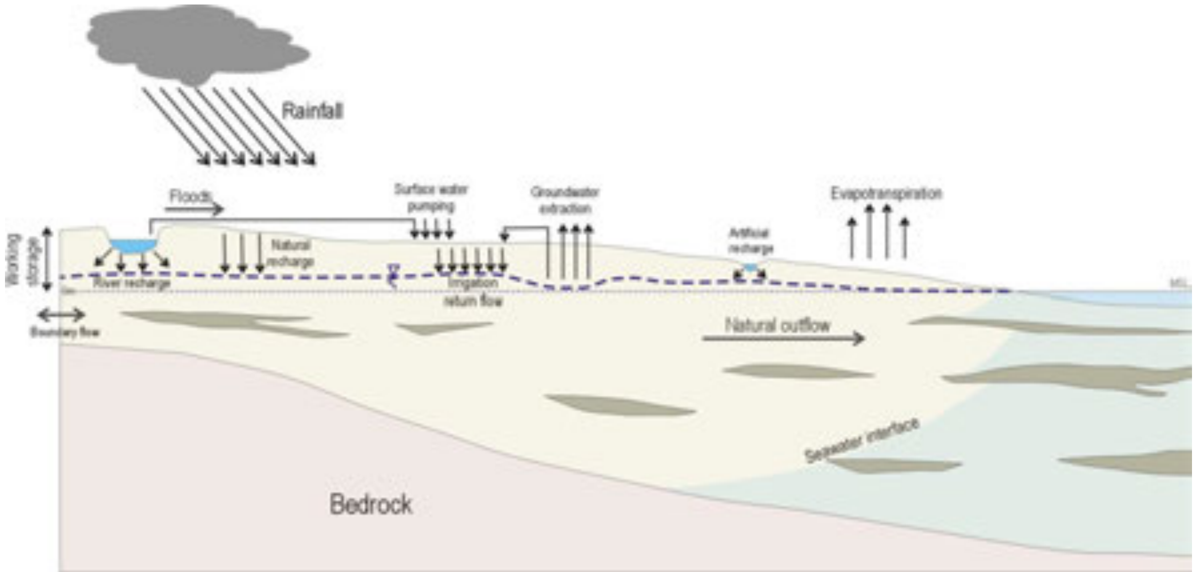


Figure 6: Water budget, Burdekin district, Australia (from McMahon et al., 2002).

The major conjunctive use regions in the Burdekin delta are managed through a separate act of the Queensland parliament. Two separate Water Boards were created covering different regions, which are controlled by a board comprising largely local water users. The board has substantial powers in the day-to-day operation of the scheme. The success of the scheme is characterized by strong and clear local 'ownership', combined with significant technical support provided by government, and has the benefit of a hydrogeologically favourable region of high-transmissivity aquifers.

3.4 Indus Basin – PAKISTAN

Pakistan's major groundwater resource is located in the irrigated areas of the Indus Basin. The hydrogeological setting can be classified as hyper-arid middle alluvial plain (Table 2). Agriculture is the single largest sector of Pakistan's economy. Due to arid conditions in most parts of the country, the contribution of direct rainfall to the total crop water requirements is less than 15 percent. The huge gap between water availability and demand is bridged via exploitation of groundwater resources.

Most groundwater exploitation in Pakistan occurs via conjunctive use with surface water. Irrigated agriculture using only groundwater is limited mainly to three situations:

- in areas not supplied by canal commands;
- in small systems outside the Indus Basin; and
- at the tail end of canal commands that have lost access to surface water through inequitable distribution of canal water supplies.

The most productive areas of the Indus Basin commonly incorporate conjunctive use of canal water and high to medium quality groundwater. Conjunctive use of groundwater and surface water allows farmers to cope with the unreliable surface-water supplies and to achieve more secure and predictable yields. However, there are adverse impacts of conjunctive use where poor-quality groundwater is used adding large amounts of salt in the root zone, and hence causing additional salinization problems to those arising from shallow water tables. In some areas, the salinity of the groundwater resource is such that there is full reliance upon canal deliveries to sustain irrigated agriculture. Even in areas where groundwater is deemed to be usable, the brackish nature of the resource commonly requires mixing with surface water prior to application to crops. However Qureshi *et al.*

(2004) noted that farmers are not fully aware of the ratios required when mixing the two water types and hence negative consequences of irrigating with high salinity water have been observed.

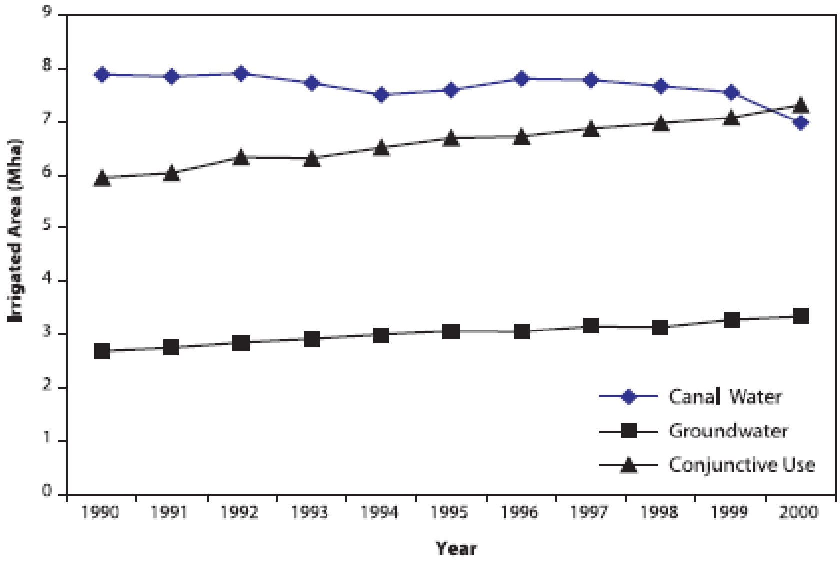


Figure 7: Increasing trend in conjunctive use, Punjab, Pakistan (taken from Qureshi et al, 2004).

The ratio of surface water and groundwater conjunctive use in irrigated agriculture identified in research undertaken by Murray-Rust and Vander Velde (1994) averaged 2:5 throughout the distributary canal command, resulting in an average irrigation-water electrical conductivity (EC) of 1 400 µS/cm. This value exceeds the current international standard that sets the upper limit for 'good' quality irrigation water at EC 700 µS/cm. To bring that average water-quality condition down to 1 000 µS/cm (still higher than the maximum value recommended by international standards), an average canal-tubewell water conjunctive use ratio of 3:4 would be required. Assuming no change in the total volume of irrigation water used in the command area, this means that the volume of canal water would have to be increased by more than 50 percent and the volume of pumped groundwater reduced by more than 20 percent of current volumes.

In addition to the technical issues, institutional challenges are also significant. Murray-Rust and Vander Velde (1994) highlight that, to halt the declining trend in sustainability of Pakistan's irrigated agriculture, "Pakistan's public agencies and supporting research institutions must begin shedding this 'historical baggage', reorganize internally and establish functional, working linkages with one another".

3.5 Other examples

Sahuquillo (2004) discusses a number of examples under the theme of alternate use of groundwater and surface water for irrigation in a more general discussion of conjunctive use. These examples are from the Mediterranean Basins of Spain and the Central Valley of California, United States of America (USA).

In the Spanish basin examples, Sahuquillo (2005) reports on the evolution of conjunctive use as a process associated with the expanding irrigation industry during wet years via surface water diversions. As groundwater resources were identified through the region, more and more groundwater abstraction was incorporated into the system. In response to an expansion in the irrigated area, more intense use of surface water during wet years increased, leading to substantial increases in overall use. These examples demonstrate a bottom-up approach that was proposed and implemented by the irrigators, which have now been incorporated into legally sanctioned schemes.

Sahuquillo (2005) discusses in more detail the status of the Mijares Basin, near Valencia, Spain. The basin is characterized by large surface water reservoirs situated over a karstic limestone aquifer, with resulting high leakage rates to groundwater. In addition, the Mijares River also leaks and recharges the local alluvial water-table aquifer. Surface water or groundwater is used as the water source depending on water availability, both in stream and in storage. The beneficial aspect of the relationship between surface water and aquifer is that, whenever more surface water is available – which is hence used by irrigators –, recharge rates to the groundwater system are higher. This provides a natural counter-cyclical process, where the groundwater resource is recharged during periods of low groundwater demand.

Bredehoeft (2011) provides some examples of conjunctive use operation in the western USA as part of a more general discussion of conjunctive use. The examples highlight the situation where surface water was generally first developed and used to its maximum to undertake irrigation – usually fully developed by the early 1900s. Bredehoeft points out that a large number of these river valleys contained alluvial deposits whose groundwater systems were well connected to the rivers. As surface water was fully appropriated, and as knowledge of the groundwater systems grew, groundwater became the new water source, and development followed in a generally unregulated fashion. Institutions to manage abstraction have evolved over time. They have, however, generally favoured prior rights in water and required the newer water users, that is, the groundwater users, to provide 'new' water to offset their pumping impacts. Consideration of opportunities to solve these challenges does not appear to have explored conjunctive resource management.

Pulido-Velazquez *et al.* (2004) and, to a certain extent, Sahuquillo (2005) discuss an interesting adjunct to the idea of conjunctive use. Both sets of authors provide examples of conjunctive use occurrences, where the surface water resource is used to artificially recharge the groundwater resource. Pulido-Velazquez *et al.* (2004) discuss the situation in Southern California, though associated with water supply projects for metropolitan areas rather than irrigation, and Sahuquillo discusses examples associated with treated wastewater near Tel Aviv, Israel, and Barcelona, Spain. Whilst not directly relevant to irrigation supplies, they do demonstrate a further type of conjunctive management that could be implemented elsewhere, presumably subject to cost.

These examples highlight a common history and common challenges. In nearly all cases where conjunctive use is being practiced (either spontaneously or in a planned manner), surface water was the dominant historical water source. Either through expansion, technology uplift, new knowledge or deteriorating water access/quality there were moves towards incorporating groundwater into the water management system. This was done either within a regulatory environment (with varying degrees of compliance) or spontaneously by individuals. The development of both water sources brings into juxtaposition the inherent difference between surface water and groundwater. Surface water is predominantly a State-owned or managed "good" that in most cases is heavily subsidized via direct infrastructure spending, as a part of national agricultural or food security policy. Groundwater, on the other hand, is rarely State-owned and managed and does not usually attract the same level of subsidy. In other words, the management of groundwater and surface water are commonly underpinned by different philosophies, differences that arguably are a significant impediment to progressing conjunctive management.

The main impediments to planned conjunctive use identified by Foster *et al.* (2010), as summarized from their work on examining a number of global examples of conjunctive use, are:

- the often disconnected responsibilities for water management between surface water and groundwater departments at various levels of government, which usually results in a failure to understand the integrative benefits of holistic resource management;
- the lack of information regarding conjunctive use management that can be used to influence and educate both politicians and the general public about conjunctive use benefits; and
- an inadequate knowledge of the degree to which privately-driven groundwater use is practiced in irrigation commands, its benefits and its risks.

4 Scope for securing social and environmental benefits through conjunctive use schemes

It is often instructive to consider where a particular approach has succeeded compared with examples where sub-optimal outcomes have been apparent. In order to gain such insight, a common understanding as to what success means within the context of conjunctive management is required.
The thread of this paper, based on others' work (primarily that of Foster and others) is that planned conjunctive use management should be a clear objective wherever both surface and groundwater resources are available. As alluded to earlier, whilst there are few examples that demonstrate effective implementation of planned conjunctive use management, spontaneous conjunctive use is common. The apparent widespread evidence of this spontaneous conjunctive use suggests that substantial financial benefits are being realized by irrigators, otherwise the practice would not prevail.

Two end-members of a possible continuum between successful attempts to retrofit conjunctive use management (which by its very nature must be planned) and areas where it is not possible to retrofit are proposed as Utter Pradesh in India and the South Platte Valley in Colorado, USA, each of which is discussed below.

In Utter Pradesh, a planned approach was implemented at the regional scale aimed at effecting changes to the water supply/demand balance by considering the nature of the complete water cycle for the area and how this behaved spatially and temporally. A series of actions were then undertaken to optimize the existing infrastructure so as to enable a larger amount of water to be accessed in a more efficient manner. It seems there was little in the way of State-sponsored investment and no apparent changes to management and/or regulation levels. However, local ownership was focused on increasing the total water availability. The benefits of these actions have been widely reported.

Conversely, within the South Platte River Valley of Colorado, the focus upon conjunctive management has been to apply existing regulations around water rights in groundwater abstraction and use, rather than considering appropriate reforms that may assist in delivering broader and longer-term water management outcomes. As Bredehoeft said (as reported above): "Effective conjunctive management can probably only be accomplished by an approach that integrates the groundwater and surface water into a single institutional framework; they must be managed together to be efficient. Current institutions based upon the present application of the rules of prior appropriation make conjunctive management not practical." This is because the existing surface-water rights are strongly maintained and enforced by the relevant water authorities and, consequently, groundwater is not able to be used in an unencumbered conjunctive-use sense.

If these two high-level summaries reflect the broader experience related to conjunctive use management then the key to successful implementation is complex and probably reliant on a mix of institutional, social, technical and economic factors that vary at the local to sovereign level.

The social, technical and economic factors require consideration within the local context, as they are critical to developing the optimum management arrangements. However, the optimum approach may prove to be purely theoretical, if implementation is inhibited by existing institutional or policy structures. This specifically applies to the legal 'ownership' of water rights, the ability of local bodies or water user associations to make day-to-day decisions and the ability to undertake effective planning for conjunctive use.
It is clear that there needs to be economic incentives to justify the adoption of conjunctive use management at both (or either of) the sovereign or individual level, independent of whether there are strong market drivers operating. As discussed briefly in previous sections of this paper, it appears that economic gain is made – where it has been assessed and reported – as a result of the adoption of conjunctive use management. This has usually been at the farm-gate level in the form of reduced costs and increased income, however economic returns may also be achieved at the sovereign level through more efficient use of the available water resource, lower subsidies to achieve the same production and increased levels of production leading to more regional development opportunities from post-farm gate multipliers. Further work to demonstrate the sovereign-level economic gains is probably warranted as part of a programme to encourage governments to commit to the institutional and policy reforms necessary to achieve adoption of planned conjunctive management at an

irrigation-command scale. For effective management, regulatory arrangements are required to include access entitlements and powers to place restrictions on the timing and volume of water abstraction.

A number of researchers have assessed and confirmed the gains to be made from conjunctive use management (for instance, see Shah *et al.*, 2006). Where economic gains have been assessed in investigations and research studies, all show positive results. This knowledge has become a major piece of evidence used to promote the implementation of conjunctive management in recent years. However, the extent of the analysis of socio-economic benefits at the irrigation-command level is limited and mainly held in unpublished reports. It is rare to see detailed analyses of the benefits and costs of conjunctive use; rather the data shows the incremental economic benefits when conjunctive use management is retrofitted to unplanned irrigation commands. In particular, it is rare to see an analysis of benefit and cost associated with planned conjunctive management, and even rarer to see a discussion of the policy and institutional approaches supporting planned conjunctive use. Very few researchers or commentators provide detail on what policies need to be put in place. It is the authors' view that this is a major impediment to the 'socialisation' of the issue across governments.

5 Governance tools that promote the adoption of conjunctive use

A range of management models exist across numerous irrigation developments around the world. Most surface-water-based delivery infrastructure tends to be in public ownership, while most groundwater relate infrastructure is farm-based and hence tends to be privately owned. The different ownership arrangements between groundwater and surface water tend to correlate strongly with the degree of commitment from governments towards management of the resource. This situation is depicted in Table 5.

Table 5: Varying ownership models and degree of management for groundwater and surface water based irrigation commands

		Public Ownership of Infrastructure (Government/State-Owned)	Part Public and Part Private Ownership of Infrastructure	Private Ownership of Infrastructure
Degree of management	Highly Managed	Common – usually surface water based	Common	Rare
	Lightly Managed	Not common	Very common	Not common
	No Management	Rare	Common	Common – usually groundwater based

Evidence of the differential attributes presented within Table 5 is apparent when considering specific examples around the world, with such differences being potentially 'cultural' in nature. For example, in most parts of India, private ownership of groundwater wells prevails, and there is minimal groundwater management, with some notable exceptions (IWMI, 2006). However in circumstances where there is communal ownership of groundwater wells, a stronger management framework is likely, albeit still very locally based.

Well-planned conjunctive use is theoretically easier to achieve with public ownership. Conversely, in a private-ownership model, stronger regulations and/or sanctions, or appropriate market mechanisms are normally required to support a transition to effective conjunctive management. However the objective should always be tailored towards providing well-planned conjunctive use models irrespective of the public/private ownership model, and whether there are centrally-regulated or market-driven environments.

One obvious market mechanism that should be considered within a planned conjunctive management regime is water trading, which requires a water allocation framework that sets limits on entitlements to sustainable levels of take. When the allocation framework has fully committed these entitlements, a trading regime – either explicitly or implicitly implemented – is an effective method to allow for redistribution of water in response to market forces. In a fully-integrated conjunctive management model, such trading regimes may enable groundwater to surface water trade (and *vice versa*), with associated rules necessarily being highly cognisant of the amount and timing of the hydraulic interaction and other attributes of the different entitlements.

Table 6: Possible management approaches to achieve planned conjunctive use for varying management models and degree of hydraulic connection between groundwater and surface water

Degree of Connection	Highly Regulated	Lightly Regulated	Free Market
Highly connected	Relatively simple management rules	General management rules necessary	Low level of management may be required – potential for optimal resource use
Moderately connected	Specific management rules required	Specific management rules required	Specific management rules required
No practical connection	Need for integrated management is more important	More involved management necessary	Complex management required – some regulation necessary

Table 6 provides a simple outline of the types of management approaches and of attempts to classify them based on the degree of connection between surface water and groundwater and on the degree of regulation of water resources by the State. The table acknowledges the continuum in (effective) regulation of the water resource and sets out broad approaches.

5.1 Required institutional structures for effective conjunctive use management

Conjunctive use management is not constrained mostly by a lack of technical understanding (though this is an important constraint), but rather by ineffective and incompatible institutional structures, with separate management arrangements, almost always established and operated by different institutions. As well, water resources at the sovereign level are often managed by a dedicated agency, whilst irrigation commands are often managed by agricultural agencies or dedicated irrigation-command authorities. Overall water resource policy may be set at a jurisdictional scale with the irrigation sector required to operate under the authority of a regulatory agency. This results in a complex mosaic of planning and decision pathways that are not easily overcome in the pursuit of a planned conjunctive management model.

Foster and Van Steenbergen (2011) acknowledge that: "In many alluvial systems, the authority and capacity for water-resources management are mainly retained in surface-water-oriented agencies, because of the historical relationship with the development of irrigated agriculture (from impounded reservoirs or river intakes and major irrigation canals). This has led to little interest in complementary and conjunctive groundwater management. Some significant reform of this situation is essential – such as strengthening the groundwater-resource management function and/or creating an overarching and authoritative 'apex' agency''. Similarly Shah *et al.* (2006) recognize that: "Water resources are typically managed by irrigation departments and groundwater departments. There is rarely any coordination between these ...".

Foster *et al.* (2010) also emphasize that: "The promotion of improved conjunctive use and management of groundwater and surface water resources will often require significant strengthening (or some reform) of the institutional arrangements for water resource administration, enhanced coordination among the usually split irrigation, surface water and groundwater management agencies, and gradual institutional reform learning from carefully monitored pilot projects. Water organizations and agencies often tend to 'mirror' historical water-supply development realities and tend to perpetuate the *status quo* and find it difficult to grasp conjunctive use opportunities. There is often considerable rigidity, and initial resistance to change." Add to this a higher-level need to align water resources and agricultural strategy, at both the sovereign and sub-regional irrigation-command level, and the enormity of the task becomes apparent.

Bredehoeft (2011) emphasizes that effective management of conjunctive use "requires integrated institutions that can plan and sustain the management of the system for long periods". This is because it typically "takes more than a decade for significant changes in groundwater pumping ... to have their full impact on the river" (as seen in the USA case he studied). Bredehoeft also stresses that, in much of the USA, the water management legal system based on prior appropriation fundamentally works against conjunctive management: "Effective conjunctive management can probably only be accomplished by an approach that integrates the groundwater and surface water into a single institutional framework; they must be managed together to be efficient. Current institutions based upon the present application of the rules of prior appropriation make conjunctive management not practical." Conjunctive use management will require major organizational change in water agencies. Furthermore reformed institutions need structures that can operate at the multiple scales with which groundwater, especially, requires.

A recent report for the World Bank (Garduño *et al.*, 2011) discussed that "The promotion of more planned and integrated conjunctive use has to overcome significant socio-economic impediments through institutional reforms, public investments, and practical measures, including: (a) the introduction of a new overarching government agency for water resources, because existing agencies tended to rigidly follow historical sectoral boundaries and thus tend to perpetuate separation rather than the integration needed for conjunctive use; (b) gradual institutional reform learning from carefully monitored pilot projects; and (c) a long-term campaign to educate farmers through water user associations on the benefits of conjunctive use of both canal water and groundwater, crop diversification, and land micro-management according to prevailing hydrogeologic conditions." These commentators reflect a view that institutional strengthening is probably the most important challenge to conjunctive use management, especially in already developed irrigation systems where a more optimized management approach needs to be retrofitted.

5.2 Optimum conjunctive management and what is meant by conjunctive use planning

Important factors to be considered in the planning process to optimize the use of groundwater and surface water are the fundamental differences between the two water sources in terms of: availability; cost, both capital and operating; and energy requirements (and hence CO_2 impacts). These three factors need to be considered individually and collectively to develop a well-planned conjunctive-use irrigation system. Of these, the different availability (as a volume) and timing between groundwater and surface water is already recognized and positively utilized in optimisation planning.

Cost differences – as usually seen by farmers – between groundwater and surface water are a key factor to be considered, with subsidies common for electricity supplies (see, for example, Shah *et al.*, 2006) impacting upon farmers behaviours (i.e. choices between surface and groundwater) and hence leading to outcomes that are not consistent with water planning objectives. In addition, the net environmental outcomes resulting from a management strategy are not yet considered in most planning frameworks, such as the CO_2 impact of different options. Many authors (for example Pulido-Velazquez *et al.*, 2006) have produced economic optimization approaches. These tend to rely on assuming that there is a water-trading regime in place that allows or encourages the redistribution of total water resources to the greatest economic good. In practice surface water to groundwater (and *vice versa*) trading regimes rarely operate across irrigation-command areas worldwide. However, such a trading approach should be encouraged as part of effective conjunctive management, noting that there are likely to be significant challenges in establishing rules that take into account the different nature of the resources. All the above factors must ultimately aim to produce the maximum crop yield per cubic meter of water used.

Part 3: Prospects

6 Prospects for slowing or reversing trends through 'governance'

The broader topic to which this paper contributes is related to groundwater governance. However, within the context of conjunctive use management, it is important to consider water governance globally, that is, governance for both surface water and groundwater. Good governance principles associated with groundwater alone still apply, but they must be made to fit a broader governance paradigm – so-called Integrated Water Resource Management (IWRM).

General water governance principles cover a number of main areas – authority, accountability, transparency, stakeholder participation and institutional integration. Authority relates to the policy and statutory powers vested in the government or delegated to an agency to administer and regulate on behalf of the government. The associated 'authority' becomes the decision-maker who must be held accountable for operationalizing policy and legislative instruments. Such an authority must be accountable for its decisions, with appropriate mechanisms in place, supportive of natural justice by enabling appeals against decisions to be independently reviewed.

As a third element, transparency is required to demystify the decision-making process, support stakeholder confidence in the management process and provide the grounds for any appeal. Participation is required to ensure that there is ownership of the process by all stakeholders; this goes a long way to achieving planned outcomes. Finally, integration (both institutional and technical) is required to ensure that all aspects of water tenure are subject to a single basic water resource regime. Water is a single resource and should be managed accordingly.

6.1 Governance approaches

It is clear that optimum water-resource use will be significantly advanced through planned management of conjunctive use in irrigation commands worldwide. There are a number of areas where the governance model is crucial to the adoption of this planned management approach. However, it is useful to note that there is no single governance model that can be applied universally; rather elements of different approaches may need to be chosen depending on the specific circumstances for each case.
Effective governance arrangements to underpin a conjunctive management strategy are deemed to be the most significant challenge. Danton and Marr (2007) in a discussion of the governance arrangements associated with the Uttar Pradesh conjunctive use example, make the point that "multi-faceted governance arrangements are necessary for successful management of smallholder surface water irrigation systems. In managing conjunctive use ... these arrangements become more complex.... The greater complexity in management arises from the need for coordinated management of the two resources through greater participation and networking of stakeholders at each stage of water allocation, use and management." Further, Livingston (2005; as referenced in Danton and Marr, 2007) subdivides water governance models for water supply systems into three types: bureaucracy, community and market. Governance approaches may favour one model, but will ultimately include elements of all three.

Garduño and Foster (2010) listed a number of challenges when considering the governance of conjunctive use management. They reported that: "Serious impediments have to be overcome to realize such water resource management policies. They are primarily institutional in character, given that the structure of provincial government organizations often simply mirrors current water-use realities and tends to perpetuate the *status quo*, rather than offering a platform for the promotion of conjunctive management."

In summary, the governance model needs to address four areas of endeavour: legislative, organisational, capacity and socio-political. In many countries, the organizational aspect may require the most significant changes to be made.

6.1.1 Institutional strengthening

Institutions that manage water, at both the national and regional scale, need to be strengthened to remove impediments. This requires the adoption of frameworks that promote IWRM where surface water and groundwater functions operate collectively towards a single overarching objective, and the function of water and agriculture ministries are also aligned for this purpose. Institutions need to be clear on who operates and manages irrigation commands; arrangements that may be inclusive of either the public or private sphere, or a combination of both.

The resolution of chain of command issues across various levels of government also needs to be reviewed. That is, each level of government must understand its role in implementing national water resource policy and be effective in enacting that role. Counter-activities at any level must be confronted and remedies provided. Institutions need to have a strong compliance culture to ensure that outcomes are achieved.

6.1.2 Policy and legislation

In many instances, there is a need to understand and review the current approaches to allocating rights in water, and the form and attributes of those rights. In many situations, policies and regulations may be poorly formulated and hence not operating efficiently to achieve the intended outcomes. Effective water allocation planning is paramount. Such planning needs to be supported by strong national policy and to occur within a framework that ensures sustainable levels of take and use of the resource. This requires significant technical input, especially within the context of the need to assess the available consumptive pool.

Conjunctive use management relies on water policies and regulations that are efficient at promoting movement of access between the two resources when required and appropriate. Legal and market powers and mechanisms must be aligned to achieve this goal.

6.1.3 Planning

By its very nature, planned conjunctive use requires a strong management platform. There is a need to clearly define objectives, outcomes, activities and performance measurement and compliance arrangements. Such plans should be based around water allocation mechanisms and have regard to the technical understanding of the total consumptive water available.

Implementation planning requires definition of investment requirements and decisions about who will make those investments, and who will ultimately pay. Ideally, planning should incorporate the triple-bottom-line notions of achieving environmental, economic and social objectives.

Conjunctive use management also requires consideration of land use policy changes so that groundwater protection outcomes can be achieved. This is not a usual set of policy decisions in most developing and developed countries and may not only require considerable input, but also political support.

6.1.4 Market and pricing approaches

Surface water and groundwater always have differential cost structures that apply to users. In centralized government systems, these cost structures may be heavily subsidized as a result of related policy decisions (for instance, those for food and energy) and there may be unwanted outcomes as a result; usually, these relate to poor water use efficiency outcomes. In general, groundwater users fully finance their associated infrastructure whereas surface water infrastructure has been either wholly or partly subsidized by the State. The different ownership models contribute to differential cost impacts for irrigators, leading to decisions that are inconsistent with optimized planning objectives. Conjunctive management needs to understand and remove these impediments. State-sponsored groundwater development is an area where investment may be required.

There are also be differences in economic approaches at the macro and micro scale, and any activity to enhance the water market needs to acknowledge the two different scales of benefits. This is also true where economic incentives are implemented.

6.1.5 On-the-ground implementation

Planned conjunctive use management will benefit strongly from, and possibly require, strong ownership by the irrigated farming sector. This can be achieved by building strong local water user groups through targeted education and enabling actions. In the past, communities have been focused upon single issues (either surface water or groundwater) and there has been a reluctance to engage in management issues associated with the other side of the resource picture that would require reorganization to better reflect the distribution of users. Overcoming this issue is exacerbated by a number of factors including the absence of a revenue base for cost recovery and the politicization of the user groups towards maintaining subsidized surface water supplies. There needs to be a participatory culture of education, demonstration and capacity building between governments and the irrigation farming community and its key stakeholders.

6.1.6 Knowledge generation

To facilitate conjunctive use management, knowledge is required in two key areas – technical understanding of the spatial and temporal distribution of the total consumptive available water and support for planning through the capability to provide future impact scenarios. The latter is generally in the form of a complex numerical model of aquifer-river basin performance. Conjunctive use management also requires the establishment or improvement of monitoring programmes so that the quantity and quality impacts of the use of surface water on groundwater and *vice versa* can be demonstrated, and so that the beneficial impacts of water management actions can be seen by all stakeholders.

6.2 Use of financial and market-based instruments to promote planned conjunctive use

Financial and market-based instruments (FMBI) are a range of financial and economic measures that can be used to encourage specific actions and trends. In the context of water resource planning, FMBI can consist in direct financial incentives (e.g. taxation reduction, subsidies to lower electricity prices) or disincentives (e.g. taxation increases) or alternatively indirect tradeoffs or offsets (e.g. pollution reduction schemes) and the introduction of water trading.

Some countries have favoured a regulatory approach to bring about various water resource outcomes, while other countries have tended to favour economic instruments, in the belief that clear financial signals are a strong lever to active policy objectives. In the case of conjunctive use, the authors are of the view that in many countries subsidies that distort the true cost of water delivery (surface water and groundwater) bias irrigator behaviours and hence retard the potential for planned conjunctive use to contribute to optimal water use outcomes.

Conversely other FMBI (i.e. those not aligned with subsidies) can be a very powerful tool to encourage the adoption of optimal conjunctive use. The range of options tends to be very location- and culture-specific. Nonetheless schemes that provide both financial incentives (e.g. through taxation decreases), when a defined minimum volume of water is used conjunctively, and indirect economic offsets (e.g. for salinity control) are considered the most effective. These should generally be used to 'kick start' planned conjunctive use and should not be seen as permanent measures.

The introduction of clearly defined water rights, the application of well defined caps (i.e. maximum limits of use of groundwater and surface water) and the introduction of a water trading regime can operate to strongly facilitate more efficient total water use. Surface-water trading regimes currently operate in many countries, however groundwater-trading regimes are not so common. Surface water to groundwater (and *vice versa*) trading regimes are rare. Nonetheless water trading can represent a strong market instrument to encourage conjunctive use, if it is managed appropriately. There are, however, few examples in the world where this has occurred. This is especially an issue where market mechanisms are not designed to account for environmental impacts (e.g. salinity effects).

FMBIs are not readily recognizable where governments exercise centralized control as opposed to a market-based approach. However, in such centralized governance approaches, positive benefit-cost outcomes through similar initiatives as FMBIs can still be achieved in terms of measures of 'national good', that is, national gross production from irrigated agriculture, poverty alleviation, etc. The issue here is about applying the most appropriate reward and compliance signals to the water/irrigated agriculture sector.

This discussion also indicates that water management policy – and its role in planned conjunctive use – is part of a larger policy position by governments that involves national food policy, poverty alleviation, economic growth, sustainability, climate change and energy considerations. Good governance is more likely to ensue once the impact on national water use policy of policy decisions (including subsidies) in these related areas is considered.

6.3 A suggested set of conjunctive use principles for consideration within a governance approach

The following is a suggested set of principles for the implementation of conjunctive use management within existing irrigation commands, where infrastructure and historical governance arrangements are in place:

- Planning should be undertaken with full and detailed knowledge of the characteristics of both the surface water and groundwater systems, of existing system operations and of the demands of the cropping systems.
- Goals should be established that are intended to optimize the water supply/demand balance, irrespective of existing institutional, governance and regulatory models.
- Revised institutional arrangements underpinning the new conjunctive management model must be supported with a strong policy and legislative base.
- The combined surface water/groundwater system and their use should be managed so as to optimize net economic, social and environmental benefits, taking into account national energy, food security, population and poverty reduction, sustainability and climate change policies and programs.
- Stakeholder participation should be encouraged.

From an operational point of view, some key guidelines to implementing conjunctive management include:

- a technically robust understanding of stream-catchment-aquifer interactions;
- a water balance that is inclusive of connectivity between the surface and groundwater systems;
- technical assessment techniques commensurate with the understanding of the hydrological system and with explicit recognition as to the limitations to the validity and applicability of information;
- a strategic monitoring programme for the catchment, including the alignment of groundwater and surface water monitoring[3].

In summary, conjunctive use planning is the structured water-planning process whereby the different characteristics (technical, economic, social and institutional) of groundwater and surface water are compared and weighed against each other so that the optimum use of the two water sources is achieved. The fact that this rarely occurs throughout the world is testament to the entrenched water institutional structures and the very poor understanding of fundamental technical processes.

[3] Monitoring regimes should recognize the differences between assessment monitoring and management monitoring. Management monitoring refers to the monitoring of management rules and processes whilst assessment monitoring refers to monitoring of the technical or scientific aspects of stream-aquifer interactions (Fullagar, 2004).

7 Conclusions

a) There is a range of settings within which conjunctive use management can occur, and there do not appear to be any situation where conjunctive use management should not be practiced.

b) Planned conjunctive use management is far better than spontaneous conjunctive use in terms of deriving a better set of outcomes from the point of view of the resource, of national good and economic return.

c) Most development has already occurred and no new ‘greenfield’ irrigation developments are likely at a significant scale, thus most implementation of conjunctive use management will be by retrofitting management arrangements to already existing systems.

d) There are major economic and social reasons to encourage planned conjunctive use, an opportunity the world cannot afford to continue ignoring.

e) Poverty reduction in irrigation areas is closely linked to water supply efficiency and hence to conjunctive use management.

f) Institutional, economic, social and technical challenges will need to be addressed, probably in that order, at the sovereign scale.

g) The regulatory settings for water management for different sovereign States will be the most important setting for management approaches. Any institutional strengthening will need to be supported by strong policy and possible legislative changes.

h) Conjunctive use management will be linked to sovereign policies related to energy, climate change adaption and to food security and hence a broader governmental approach will need to occur.

i) An important part of planned conjunctive use is the identification of the true total cost of water resources and the separate cost to individual users (for example, electricity subsidies are very common), which can greatly differ.

j) The degree of connectivity of surface water and groundwater is an important technical consideration, but not one that will greatly influence whether conjunctive use management is successful.

k) Institutional strengthening around groundwater management and a fully integrated water agency will be a major challenge in most areas.

l) A minimum standard for conjunctive use management is the presence of some form of institutional arrangement related to groundwater management, which addresses issues such as sustainability via some form of regulation.

m) Public education and supporting technical assessments is an important part of conjunctive use management.

n) Approaches that generate the greatest degree of flexibility in water management are to be encouraged.

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Urban-Rural Tensions and Opportunities for Co-Management

Digest

Relevance

Sustained population growth has placed an enormous burden on global water supplies. In many regions, rapidly expanding cities requiring water for drinking, sanitation and industry compete with the agricultural sector that requires water to provide the very same burgeoning cities with adequate food. Groundwater is a particular concern as it represents over 95% of the world's available fresh water reserves and continues to play a major supply role in many of the world's cities. It is estimated that over 1.5 billion urban dwellers currently rely on groundwater and this number is likely increasing due to the generally modest cost of water wells and the close, "well's length" proximity of the resource.

Within 20 years, the global population is projected to rise from 7 billion to 8 billion with this entire growth taking place in urban areas. By 2050, the world's <u>urban</u> population is expected to reach 6.3 billion at which time the world's urban population will be the same as the world's <u>total</u> population in 2004. Most of the growth will occur in developing countries, where relatively well-serviced population centres are surrounded by expanding stretches of under-serviced suburbs and peri-urban slums where groundwater is often the only source of water supply. Some peri-urban settlements support as many as 70% of the city population, many living in abject poverty with squalid, sub-standard, housing and no security of tenure. Since there is no international agreement on how to define "urban" limits, many suburban and peri-urban areas remain seriously neglected when it comes to urban planning and the provision of adequate water services. In many cases, there is simply no urban planning at all. Without the planning of urban space and infrastructure, opportunities to provide adequate water and sanitation services are seriously compromised. Left unaddressed, urban slums threaten both national and international security, human health, and environmental sustainability.

Scope

This thematic paper examines urban-rural tensions and opportunities for co-management. Focusing on rapidly growing cities in low- and middle-income regions of the world, it provides a macro view of how urban-rural tensions develop, and how appropriate structures of governance can reduce conflict and eliminate, or at least ameliorate, the problem. Discordance over water is no stranger to the urban environment and the addition of a rural dimension adds an unwelcome level of complexity to the task at hand. Studies in India suggest that conflicts typically arise due to:

- Quantity, with conflicts developing between sectors or users (e.g. agriculture vs. domestic; municipality vs. industries or private users; urban vs. peri-urban or rural).
- Quality, with conflicts arising from the threat of water that is unsafe to drink.
- Access, with conflicts over water rights, price or simply physical accessibility to a water source.

In many respects, the rural-urban interface represents a veritable breeding ground for water conflict as it often forces into co-existence groups with diverse socio-cultural backgrounds and disparate needs and ambitions. Moreover, many of these groups tend to be informal and marginal. They lack community structure, have few legal rights and enjoy little or no political representation. As a result they are deprived of institutional support that could respond to their needs.

Constraints and key things to know

History shows that where urban water delivery services are positively planned, centralised systems of water service approach often fail. Where countries have adopted a "decentralised" approach, these have shown mixed success with affluent residents often enjoying significantly better access to water services than the poor or those from rural areas. In many cases, decentralization has failed because financial resources have tended to remain at the central level and the transfer of important decision-making responsibilities to district and village levels has not been followed by the transfer of funds for essential capacity development.

A compounding problem in the global effort to supply growing cities with adequate water services has been the failure to show respect for the fundamental differences that exist between surface water and groundwater as sources of supply. The "global urban water crisis" has been high on the global water sector agenda for more than twenty years and the lack of good water governance has been frequently cited as an underlying problem in urgent need of attention. However, virtually all the debates on global water policy that have raged at international water meetings in recent decades have remained transfixed on surface water issues with the role and importance of groundwater frequently ignored. Integrated Water Resources Management (IWRM) and its multi-faceted, integrative approach to water systems management has been widely publicised as the solution to the world's water issues, but has not served us well in the urban areas of the world. This is because IWRM gives very little recognition to the vital function that groundwater plays in the global water cycle and the immense benefits that could be derived from the improved management of groundwater. A failure to recognise the unique and special attributes of groundwater represents one of the lost opportunities of IWRM.

To some extent, the neglect of groundwater reflects an "out of sight, out of mind" mentality which has promoted ignorance for water movement in the subsurface. However, neglect has also arisen because groundwater and surface water systems are spatially distinct and, in terms of water flow velocities, operate on totally different time scales. Reasons aside, the unfortunate consequence is that tools for urban water management rarely, if ever, incorporate an adequate understanding of aquifers either during the analysis stage or, just as importantly, during the subsequent management decision-making. For example, groundwater resources are highly dependent upon land-use in the main 'aquifer recharge areas' such that any change in land-use can significantly affect both the rates and quality of recharge. This means that groundwater governance cannot be adequately addressed without considering the processes that determine land-use. In urban areas land-use classification and control are generally the domain of municipal or local government, and the absence of mechanisms whereby water resource agencies can influence the process is a frequent governance weakness. Similarly, groundwater supply for many urban areas is obtained from peri-urban well fields such that rural land-use practices and the intensification of agricultural production (largely controlled by national agriculture and food policy) exert a very strong influence on groundwater recharge rates and quality. There are currently no established procedures or incentives for the resource interests of an urban municipality to be assumed and maintained by a neighbouring rural municipality, such that adequate protection can be offered for the capture area of the external wellfield.

Prospects and key recommendations

Some excellent work has been conducted on groundwater governance during the past ten years, notably by the World Bank's Groundwater Management Advisory Team (GW-MATE) and others. This work has raised the profile of groundwater in the political arena and drawn attention to the widespread use of groundwater in many of the world's most impoverished cities. It has also has provided blueprints for building appropriate governance structures, the parties involved and the various roles that must be played. These blueprints are founded on a realisation that current problems with urban groundwater management will be resolved only if governments work in association with groundwater users rather than attempting to regulate and control them.

Good urban groundwater governance and the development of appropriate groundwater management action plans must begin with a fundamental understanding of the resource setting. The resource setting will include both the hydrogeological conditions (aquifers, recharge rates, economic reserves and vulnerability to pollution) and the socio-economic situation (demand, users, and groundwater-use drivers such as well construction costs and energy subsidies). In turn, a sound knowledge of the resource setting will lead to the identification of various management measures related to:

a) the supply side (e.g. recharge augmentation and conjunctive use);
b) the demand side (e.g. water use tariffs), and
c) sustainable water quality (e.g. aquifer vulnerability mapping and pollution pressure control in well head protection areas).

It is essential that the technical capacity to deliver the necessary knowledge base is in place. National governments need to ensure state/provincial/municipal level agencies receive adequate funds to hire and retain the well trained professionals required to perform the necessary work. Whichever model of governance is adopted for urban groundwater management, there can be no substitute for a sound knowledge and understanding of the aquifer system.

Ultimately, good governance and the successful implementation of urban groundwater management plans require the establishment of appropriate institutional frameworks. These would normally include departments and agencies at the national and/or state level working interactively with regional and city governments. The latter would normally be obliged to help execute national/state policies while assuming various degrees of responsibility for the provision of water services and the development/implementation of water management plans. Many institutional models can be found and clearly, there is no "one-size-fits all". GW-MATE operational experience lends favour to a decentralised approach to groundwater management that includes effective stakeholder participation. They warn, however, that attempts to modify legal provisions and organizational arrangements for groundwater governance can be politically difficult and time consuming, and suggest that in many cases a pragmatic, dual pronged approach is required that seeks to forge progress within the existing framework, while working in parallel on appropriate legal reforms.

Since a primary goal of groundwater management is to influence the behaviour of individual groundwater users and potential polluters, the value and importance of stakeholder participation cannot be over-emphasised. It is a critical instrument of groundwater governance in the broader sense and is especially appropriate in urban settings. This is because:

- Top-down management decisions taken unilaterally by regulatory agencies without broad social consensus are often impossible to implement; stakeholders need to feel a sense of ownership in groundwater management plans and share in the responsibility for all decisions that are made.
- Important groundwater management activities such as monitoring, policing and tariff collection can be carried out more efficiently and more economically through cooperation.
- Stakeholder participation facilitates the integration and coordination of decisions relating to groundwater resources, land use and waste management.

Very few groundwater-dependent cities obtain adequate water supplies from within city limits, but those that do have a dire need to maximise the quantity of the available resource while safeguarding water quality. Unfortunately, there is all too often a vacuum of responsibility and, therefore a lack of accountability, for urban groundwater. At best, responsibility for the sustainability of groundwater supply is divided between a number of organizations, none of which is normally willing, indeed capable of taking the lead necessary for coordinated management action. Typically these organizations include municipal water-service utilities, provincial/state government water-supply and public-health engineering departments, central and/or provincial/state/basin groundwater resource agencies and environment protection/pollution control agencies. Municipal water-service utilities are usually best equipped to handle the engineering of water-well construction and operation, but rarely show interest in understanding and managing the resource base. It means that the criteria for water-well siting and construction are normally based on efficiencies of cost and are not considered in terms of optimal use of the groundwater resource. It is often said that "urban groundwater tends to affect everybody, but is the responsibility of 'nobody'." This clearly needs to change. A much more integrated approach to urban water-supply, mains sewerage provision and land-use is required to avoid persistent and costly problems. It is important that solutions to issues in one sphere do not simply create problems in another.

Most groundwater-dependent cities are ultimately reliant on external aquifers over which they may have little, if any, jurisdiction or influence. Recognising the huge demand for groundwater in rural areas to meet agricultural needs, an unhealthy competition for the resource is emerging in many towns and cities, with those living at the rural-urban interface (RUI) and in peri-urban areas at the heart of the conflict. Not surprisingly, there are two diametrically opposed perspectives to this urban-rural issue and there is an urgent need for cities to work with peri-urban and rural communities to ensure that resources are adequately protected and that the needs of all parties are adequately met. While this can be achieved to some extent by broad stakeholder participation, the ultimate challenge will be to develop aquifer management plans that provide for rural-urban co-management. While co-management of urban and rural groundwater is a worthy goal with many potential benefits for all users, this would need very significant reform of current institutional arrangements together with a closer re-alignment of management objectives. Important first steps should include increased public awareness, concerted dialogue amongst stakeholders and data-sharing between agencies that have an interest in water management. The starting point for co-management and the resolution of urban-rural tension is co-operation.

Thematic Paper 3

URBAN–RURAL TENSIONS AND OPPORTUNITIES FOR CO-MANAGEMENT

By

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1 Introduction

1.1 Origins of urban-rural tension

Sustained global population growth (Figure 1) has placed an enormous pressure on planet Earth's finite resource of fresh, available water. In many countries, increasing competition for water between agriculture, industry and domestic needs, threatens economic development, food security, livelihoods, poverty reduction and the integrity of ecosystems. Rising demand for groundwater is a particular concern as, in many areas, groundwater production exceeds the level of sustainability (Jones, 2011). By far the biggest rivals in the global water supply contest are:

- the rapidly expanding towns and cities which support over half the world's population and require water for industry, potable supply and sanitation (Chilton, 1997 and 1999; Howard, 2004 and 2007), and
- the agricultural sector which already consumes some 70% of available resources, much of it to fuel Asia's "green agricultural revolution" (Evenson and Gollin, 2003; Giordano and Villholth, 2007; Jones, 2010).

By 2030, the global population is projected to reach 8 billion (from 7 billion today) with a concomitant increase in demand for irrigation water, while the proportion of the population living in urban areas is expected to rise to almost two thirds. Much of this growth will occur in low- and middle-income countries where the availability of groundwater can be an important catalyst for economic development. Urban-rural tensions are an inevitable consequence of growth, with the most serious risk of conflict[1] occurring at the rural-urban interface (RUI) and in peri-urban areas (Figure 2), where groundwater is often the only source of water supply (Foster *et al.*, 2000).

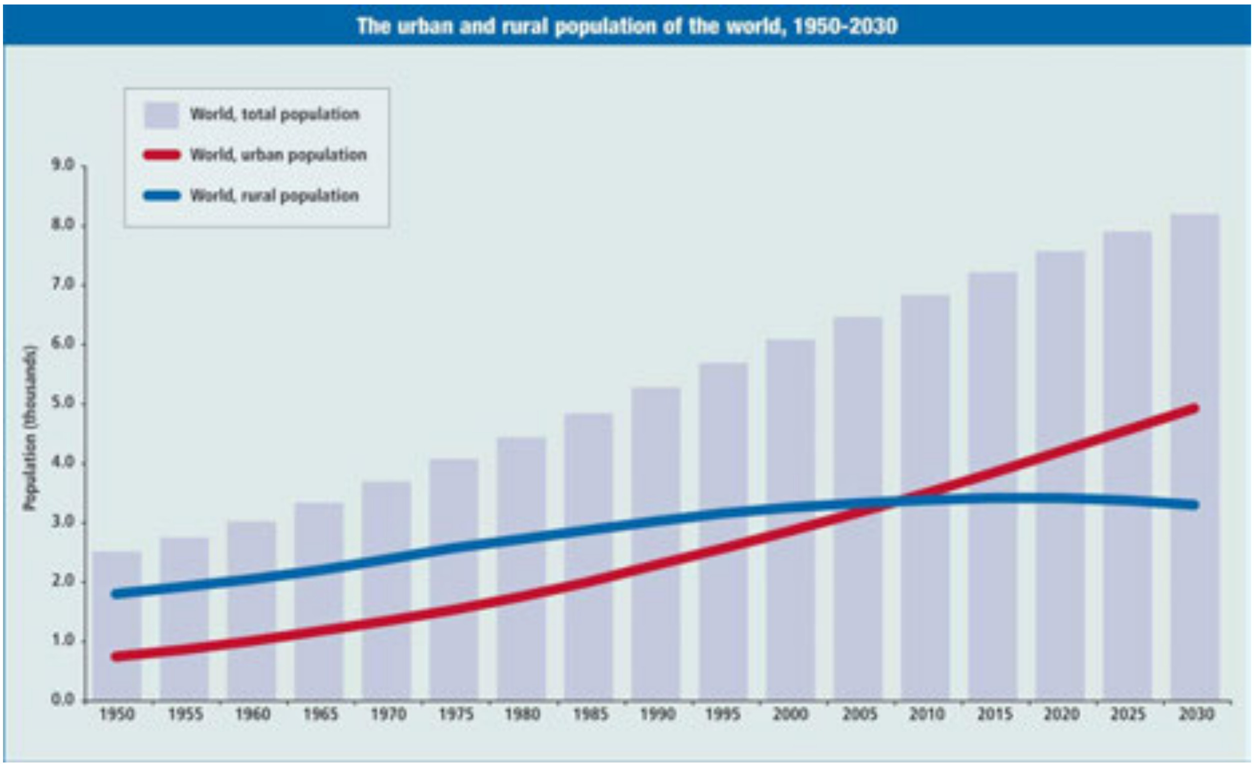

Figure 1. Global and urban population growth (from the UN, 2006)

Much of the growth has occurred during the past 40 years. In 1950, the world had just 75 cities with over 1 million people and, by 1975, only Tokyo, New York and Mexico City had reached "megacity" status with populations above 10 million. By 2010, the world had 21 megacities (Table 1) (UN, 2010a), a number that is expected to increase to 29 within 15 years. The greatest rates of megacity growth are being experienced in Lagos (Nigeria),

[1] A conflict implies an opposition between at least two categories of actors whose interests are temporarily or fundamentally divergent (Janakarajan et al., 2006). We shift from a tension to a conflict when a verbal, legal or physical confrontation leads to one of the parties implementing a credible threat. Conflicts are normally classified as economic, environmental, social or political.

Dhaka (Bangladesh) and Karachi (Pakistan) with rates well above 2% per annum (UN, 2010b). These are closely followed by the megacities in India (Delhi, Kolkata and Mumbai) and in the Philippines (Manila). In China, less than 20% of the population lived in cities as recently as 1980. By 2011, over 50% of China's population lived in urban areas, a figure that analysts predict will increase to around 70% by 2030.

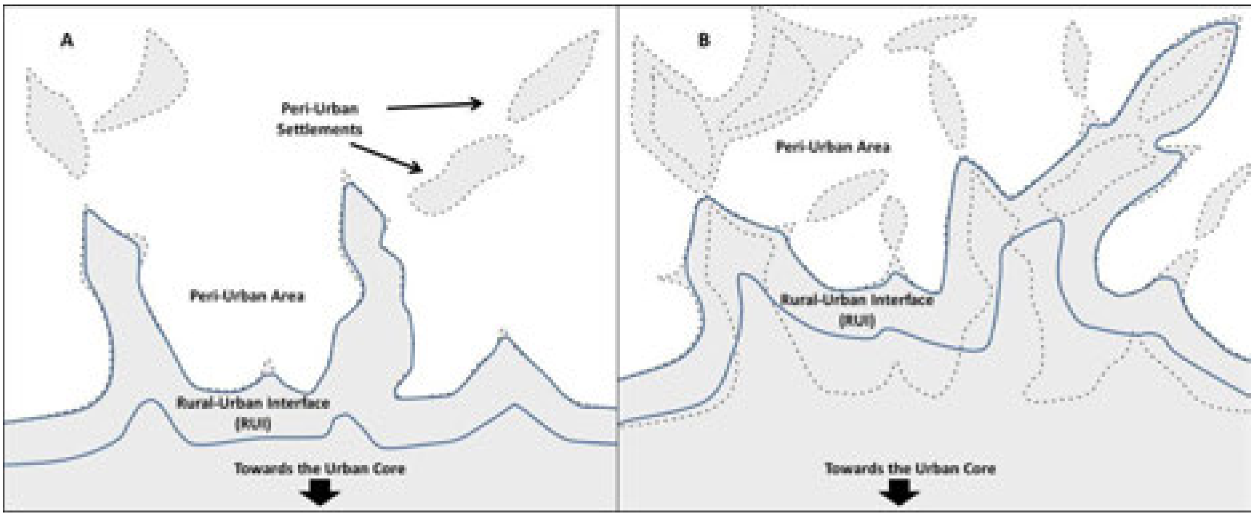

Figure 2. Two stages of urban expansion (A and B). Shaded areas are populated. *The rural-urban interface (between the solid lines) and the peri-urban area are shown. Note how peri-urban settlements eventually get absorbed into the urban area and new, peri-urban settlements grow.*

Table 1. The world's 21 megacities (data from the UN, 2010a)

City	Country	Population (Millions)
Tokyo	Japan	36,67
Delhi	India	22,16
São Paulo	Brazil	20,26
Mumbai (Bombay)	India	20,04
Ciudad de México (Mexico City)	Mexico	19,46
New York-Newark	United States of America	19,43
Shanghai	China	16,58
Kolkata (Calcutta)	India	15,55
Dhaka	Bangladesh	14,65
Karachi	Pakistan	13,12
Buenos Aires	Argentina	13,07
Los Angeles-Long Beach-Santa Ana	United States of America	12,76
Beijing	China	12,39
Rio de Janeiro	Brazil	11,95
Manila	Philippines	11,63
Osaka-Kobe	Japan	11,34
Al-Qahirah (Cairo)	Egypt	11,00
Lagos	Nigeria	10,58
Moskva (Moscow)	Russian Federation	10,55
Istanbul	Turkey	10,52
Paris	France	10,49

By 2050, the world's urban population is expected to increase by 84% to 6,3 billion. At this time, the world's urban population will be the same as the world's total population in 2004. Virtually all the global population growth will be concentrated in the urban areas of the developing world, which are projected to see a rise in population from 2,5 billion in 2009 to 5,2 billion in 2050 (Figure 3). While much of the growth will be driven by a natural excess of births over deaths, part will involve the migration of rural inhabitants who are either attracted to the opportunities urban areas can provide for alleviating poverty and improving living conditions, or are forced to move in response to political conflict and environmental crises (WWAP, 2009). An even smaller part will involve rural inhabitants living just beyond the rural urban interface (RUI) who simply become absorbed into urban areas, as urban limits expand and rural lands are engulfed. Currently, there is no international consensus on how to define where "urban settlements" begin and where they end. This leads to unclear assignments of responsibility and can seriously impede decision-making. As a consequence, many peri-urban areas are simply neglected by city planners and remain unregulated (Ahmed and Alabaster, 2011).

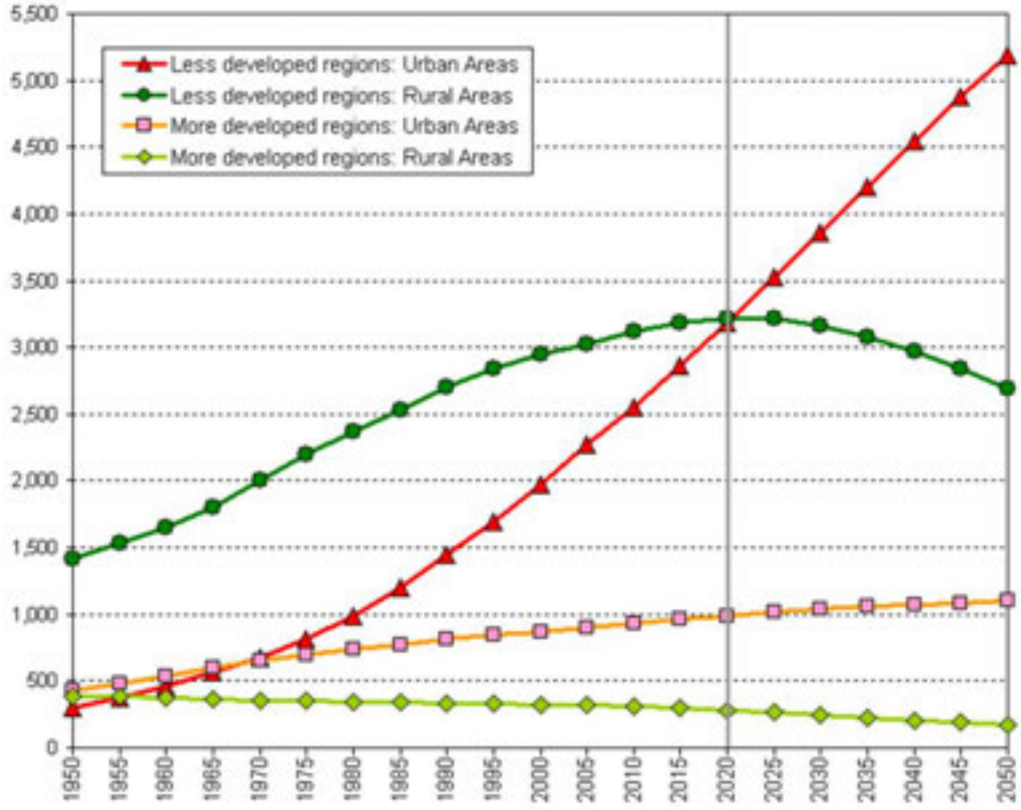

Figure 3. Urban and rural population change for the more developed and less developed regions of the world (in millions) (from the UN, 2006).*Beyond 2020, the population of urban areas is projected to exceed the population of rural areas, for the less developed regions.*

In the developing world, it is the rural inhabitants who are amongst the most destitute (IFAD, 2001), and it is those living close to the RUI and the peri-urban settlements (Figure 2) who are most seriously threatened by rapid urban growth. For many rural inhabitants, access to a secure source of groundwater provides the only means of escaping abject poverty. Because of its relative ease of extraction, almost ubiquitous extent, negligible treatment requirements, low susceptibility to drought (Calow *et al.*, 2002) and minimal infrastructure costs in comparison to surface water (Llamas *et al.*, 1998), groundwater provides the rural poor with the prospect of generating income as well as meeting domestic needs. At the RUI, the security of essential groundwater supplies is seriously compromised. Rural inhabitants, and particularly the rural poor, face numerous challenges including:

- strong competing demand for groundwater from urban and industrial users including the risk of rapid water level decline due to high-yield municipal wells;
- the threat of groundwater contamination due to urban runoff or leaching of contaminated water from urban pollutant sources such as sewage (Nagaraj, 2005);
- an inability to influence water allocation due to a lack of representation in positions of political and economic power (Torres, 2007; Werna *et al.*, 1998);
- increased risk to livelihoods from extreme events – droughts and floods, from greater climatic variability and climate change.

1.2 The governance challenge

This thematic paper examines urban-rural tensions and opportunities for co-management. It provides a macro view of how urban-rural tensions develop in various domains and how the development of appropriate structures of governance[2] can reduce conflicts and eliminate, or at least ameliorate, the problem. The role of governance has recently acquired significant meaning and attention within the water sector (World Water Assessment Programme (WWAP), 2003, 2006 and 2009). The concept has evolved from a political taboo in North-South development co-operation dialogue to gain wide acceptance as a fundamental issue at global, national and local levels. The framing of water challenges in terms of governance has allowed a broadening of the water agenda to include the scrutiny of democratization processes, corruption, power imbalances between rich and poor countries and between the rich and the poor (Tropp, 2006a). Governance and politics have become recognized as integral components of the water crisis, as well as part of its solution.

Discordance over water is no stranger to the urban environment (e.g. UNESCO, 2006) and the presence of a rural dimension adds an unwelcome level of complexity to the task at hand. Based on studies in India (Janakarajan *et al.*, 2006) conflicts typically arise due to:

- quantity, with conflicts arising between sectors or users (e.g. agriculture *vs*. domestic; municipality *vs*. industries or private users; urban *vs*. peri-urban or rural);
- quality, with conflicts arising from the threat of water that is unsafe to drink;
- access, with conflicts over water rights, price or simply physical accessibility to a water source.

In many respects, the rural-urban interface represents a veritable breeding ground for water conflict as it often forces into coexistence groups with diverse socio-cultural backgrounds and disparate needs and ambitions. Moreover, many of these groups tend to be informal and marginal. They lack community structure, have few legal rights and little or no political representation. As a result they are deprived of institutional support that could respond to their needs.

1.3 Thematic paper approach

The thematic paper comprises three major chapters. Chapter 2 (below) provides baseline information for the paper and describes the existing state of groundwater governance as it relates to the urban environment and urban-rural relationships. The chapter examines the types of tension and conflict that arise over water in urban areas, thereby highlighting the underlying governance issues that must be addressed. In Chapter 3, the tensions and conflicts are analysed in further detail using specific examples from around the world. Here, the objective is to develop an understanding of the extent, nature and root causes of urban-rural tension, and the opportunities to resolve, or at least moderate, the problem through cooperation and good governance. The governance issue is explored in greater detail in Chapter 4 where appropriate models of governance are examined and opportunities for urban-rural co-management of groundwater are discussed. Conclusions are briefly drawn in Chapter 5. The paper draws heavily on material previously published by individual authors and agencies. The sources of this material are provided in the closing bibliography.

[2] *Water Governance refers to the range of political, social, economic, and administrative systems that are in place to develop and manage water resources and the delivery of water services at different levels of society. It comprises the mechanisms, processes, and institutions through which all involved stakeholders, including citizens and interest groups, articulate their priorities, exercise their legal rights, meet their obligations and mediate their differences.*

2 Baseline

Water issues related to urban growth have been well documented, with poor water governance frequently cited as the root cause of the tensions and conflicts that arise. Unfortunately, the vast majority of urban water studies and "in-depth" analyses have considered water management in the broader sense, with little effort made to articulate the important distinctions between groundwater and surface water as water supply sources and how such differences must influence water governance. In this chapter (Chapter 2), the relationship between urban water conflict and governance in cities is reviewed, highlighting the particular plight of those living within the rural-urban interface and peri-urban areas.

2.1 Urban water management - a global review

Concern for urban population growth and the need to address increasing demand for water in novel, yet sustainable ways, has been high on the global water sector agenda for more than twenty years. First explicitly embraced in the Dublin Statement on Water and Development (1992), the formidable challenge of supplying rapidly growing cities, with adequate supplies of water for drinking and sanitation, has since remained a topic of continuous discourse. It has featured strongly at recent World Water Fora (The Hague, 2000, Kyoto, 2003, Mexico, 2006 and Istanbul, 2009) and has formed a major component of UN World Water Development Reports (WWAP, 2003; 2006; 2009). Between 2002 and 2007, urban water issues were examined in some detail during the 6th Phase of UNESCO's International Hydrological Programme (IHP-VI Focal Area 3.5 "Urban areas and rural settlements"), and between 2000 and 2010, the protection and management of groundwater in urban areas represented a major focus of the World Bank's Groundwater Management Advisory Team (GW-MATE) and resulted in numerous briefing notes, case profiles and strategic overviews (see Foster *et al.*, 2010a, 2010b and 2010c), together with important contributions to the peer-reviewed journal literature (e.g. Kemper, 2004; Foster *et al.*, 2011).

The series of urban water projects implemented under UNESCO's IHP-VI culminated in an International Symposium on "New Directions in Urban Water Management", which was held in Paris during September 2007. This meeting concluded with the adoption of "The Paris-2007 Statement on New Directions in Urban Water Management" which contained a summary of its main deliberations and built strongly on the findings of previous World Water Fora and key international conferences, e.g. the Beijing Declaration and Platform for Action (UN Fourth World Conference on Women, 1995), the Paris Statement of 1997 (Symposium on Water, City and Urban Planning, 1997), the United Nations Millennium Declaration (2000), the Marseille Statement (UNESCO Symposium on Frontiers in Urban Water Management: Deadlock or Hope?, 2001), the Johannesburg Plan of Implementation (World Summit on Sustainable Development, 2002) and the UN CSD-13 policy recommendations on practical measures and options to expedite implementation of commitments in water, sanitation and human settlements (13th session of the United Nations Commission on Sustainable Development, 2005). The Paris-2007 Statement re-emphasised the stress placed on water resources by unprecedented rates of population growth and urbanization, and drew attention to a "widespread crisis of urban water governance, particularly in developing countries", noting the following:

- fragmented institutions (geographically and across different aspects of the water cycle);
- weak regulatory and institutional frameworks, excessive centralization, an unclear division of responsibilities between the central and local governments, inefficient and outdated management practices, and misguided decision-making due to short-term political or commercial interests that lead to inadequate capacity to address urban water challenges;
- limited user participation, leading to inequality among the urban population served by water services and an increasing number of urban water conflicts.

The Paris-2007 Statement stressed the need to adopt new approaches to water management in urban areas, approaches that might include:

- practising the protection and sustainable management of groundwater, as an indispensable source of water supply for a large part of the world's population;
- moving away from water-supply management alone to water-demand management;

- understanding and accounting for the complex socio-economic issues associated with urban water management (e.g. concepts such as social inclusion, affordability, user participation, preferences and acceptability);
- drawing the distinction between water as a service and water as a resource, especially with respect to conflict resolution (the lack of such a distinction is the root cause of many urban water conflicts and is a key consideration for water rights and allocation issues); and
- adopting an integrated and participatory approach to urban water management by engaging with a wide circle of stakeholders from users (customers) to professionals (planners and builders), through learning alliances where appropriate.

The Paris-2007 Statement concluded that sustainable urban water management should be based on several key concepts, including: 1) enhancing resilience of urban water systems to global change pressures; 2) making interventions over the entire urban water cycle; 3) invoking demand management including a reconsideration of the way water is used (and reused); 4) making more prudent use of existing infrastructure; 5) making more frequent use of local and natural systems; 6) improving governance and financial management structures; and 7) promoting more active stakeholder participation. In particular, it was recommended that higher priority be given to the protection and holistic management of groundwater and that technological innovations such as advanced water and wastewater treatment processes, grey water reuse and eco-sanitation be adopted in cooperation with stakeholders, who could help overcome technological, institutional and economic barriers to sustainable water management measures.
The IHP-VI urban water studies also led to a compendium of essays (UNESCO, 2006) that focused on water conflicts in a broad range of urban settings. This work (parts of which are analysed in Chapter 3) found that most urban conflicts involve (Barraqué, 2006):

- quality/extension of drinking water services and their continuity;
- quality/extension of waste-water collection and treatment;
- urban hydrology problems (storm water control);
- impact of large cities upon their environment, in particular water resources use and misuse;
- financing of investments issues;
- tariff setting and cost recovery; and
- degrees of freedom left to urban dwellers vis-à-vis the services provided.

However, the document also revealed stark differences between developed and developing countries on a range of issues, mostly related to commodification, i.e. the commercial character of the service which is widely accepted in the developed world, but is highly contentious in countries where a significant proportion of the population cannot afford to pay for services. Many low- and middle-income countries were also found to suffer from water scarcity, such that the most common sources of conflicts were:

- lack of access to clean water sources for the poor;
- quantities of water available for public services (reallocation issue of water rights); and
- quality issues that result from either overexploitation or industrial pollution (the decreasing quality of raw water implies growing treatment costs).

Recent UN World Water Development Reports (WWAP, 2006 and 2009) have continued to blame urban water problems on inadequate water governance, noting that in many cases, corruption[3] has seriously undermined efforts to improve governance systems. Within public service institutions for water, corruption remains one of the least addressed challenges. Frequently ignored and tacitly accepted, corruption was once seen as a 'necessary evil' that could on occasion 'grease the wheels' of development efforts (Tropp, 2006b). Today corruption is seen as a scourge that must be defeated (Stalgren, 2006). It can be manifest in many different ways, and its scale may vary substantially across types of water practices and governance structure according to the perceptions and moral values of actors involved. However, the negative consequences of corruption are unequivocal (UNDP, 2004; Tropp, 2006b):

[3] The United Nations Development Programme (UNDP) defines corruption as "the misuse of public power, office or authority for private benefit – through bribery, extortion, influence peddling, nepotism, fraud, speed money or embezzlement. Although corruption is often associated with government and public servants, it also prevails in the private sector". Corruption concerns not only the exchange of money and services, but also takes the form of cronyism, nepotism and various kinds of return for favours (Transparency International, 2004; UNDP, 2004).

- It reduces economic growth and strongly discourages water sector investments.
- It undermines the performance and effectiveness of both the public and private sectors, leading to inefficient and unequal allocation and distribution of water resources and related services.
- It decreases and diverts government revenues that could be used to strengthen budgets and improve water and other services, especially for poor people.
- It breeds impunity and dilutes public integrity. It renders rules and regulations ineffective, often leading to uncontrolled water pollution, overpumping and depletion of groundwater, lack of planning, degradation of ecosystems, and unrestrained urban expansion leading to heightened water tensions. Discretionary powers and uncertainties in policy and law enforcement create unpredictability and inequalities and can also lead to complete circumvention of the rule of law and justice system.

Corruption is symptomatic of poor governance. It is also a primary reason why reforms of governance systems have been slow to materialize and gain acceptance.

2.2 Incorporating the special and unique attributes of groundwater

Another important impediment to the reform of urban water governance has been a systemic failure to acknowledge the special and unique attributes of groundwater, attributes that demand special attention when it comes to water management. Groundwater and surface water derive from the same atmospheric source (precipitation), and are indistinguishable when they emerge from a pipe in the home, factory or farmer's field. However, that is where the similarities end. Although they share the same water cycle, groundwater and surface water behave on very different spatial and time scales (Table 2) and require approaches to resource management that are quite distinctive (Theesfeld, 2010) and rarely fully understood. In terms of this paper, the challenge is to ensure that the special and unique attributes of groundwater are adequately appreciated and appropriately acknowledged in models of urban water governance.

Table 2. Essential differences between surface water and groundwater (modified after Puri and El Naser, 2003)

Rivers	Aquifers
Long, linear features.	Bulk 3-dimensional systems.
Use of resource either limited to close to the river channels or requires transport via pipeline.	Aquifers naturally convey resource to within one well's length of users.
Replenishment always from upstream sources.	Replenishment may take place from any or all directions.
Rapid and time limited gain from replenishment. Limited storage – prone to drought.	Slow response to replenishment. Very large natural storage allowing net gain to be drawn upon over long time period. Resilient to drought.
Little opportunity to manipulate storage within river body.	Unlimited opportunity to manipulate storage in aquifer body.
Abstraction has an immediate downstream impact.	Abstraction impact in any or all directions and slowly manifest over years and decades.
Little impact on upstream riparian.	May have an equal impact on both upstream and downstream riparian.
Pollution impacts transported downstream rapidly (order of metres per second).	Very slow movement of pollution (order of metres per year).
Pollutant transport invariably downstream, upstream source may be unaffected.	Pollutant transport controlled by local hydraulics. An operating well may induce upstream movement of pollution towards itself.

Groundwater represents, by far, the world's largest and most ubiquitous source of fresh accessible water. It therefore comes as no surprise that many of the world's most populated cities can attribute their early origins to the good quality groundwater obtained from shallow private wells. Where available, groundwater is generally favoured over surface water since it is well protected from surface contaminants, is less susceptible to drought and climatic variability and can be introduced incrementally, one well at a time, to meet growing private, municipal and industrial demand with minimal upfront capital expenditure. Research has shown that most urban areas evolve through a series of distinct stages as they gradually age (Morris *et al.*, 1997). Associated with these stages are developments in infrastructure, most notably related to water supply systems and sanitation. The early stages begin with the village or small settlement that gradually grows into a market town (Barrett and Howard, 2002). Subsequent stages include rapid industrialization and urbanization, which is followed by suburbanization as the population becomes decentralized. During early stages of development, water is normally supplied by shallow, unplanned private wells in a generally central location; on-site sanitation is the primary method of disposal for human waste. As growth accelerates, the settlement commonly experiences severe degradation of shallow groundwater quality associated with a slow decline of water levels, conditions observed in many emerging cities today. Deeper wells, initially for municipal use and later for industry often provide a temporary solution, but eventually there is a shift towards new supply wells developed in increasingly remote peri-urban areas (Morris *et al.*, 1997) (Figure 4). At this stage, the city has become a major net importer of water.

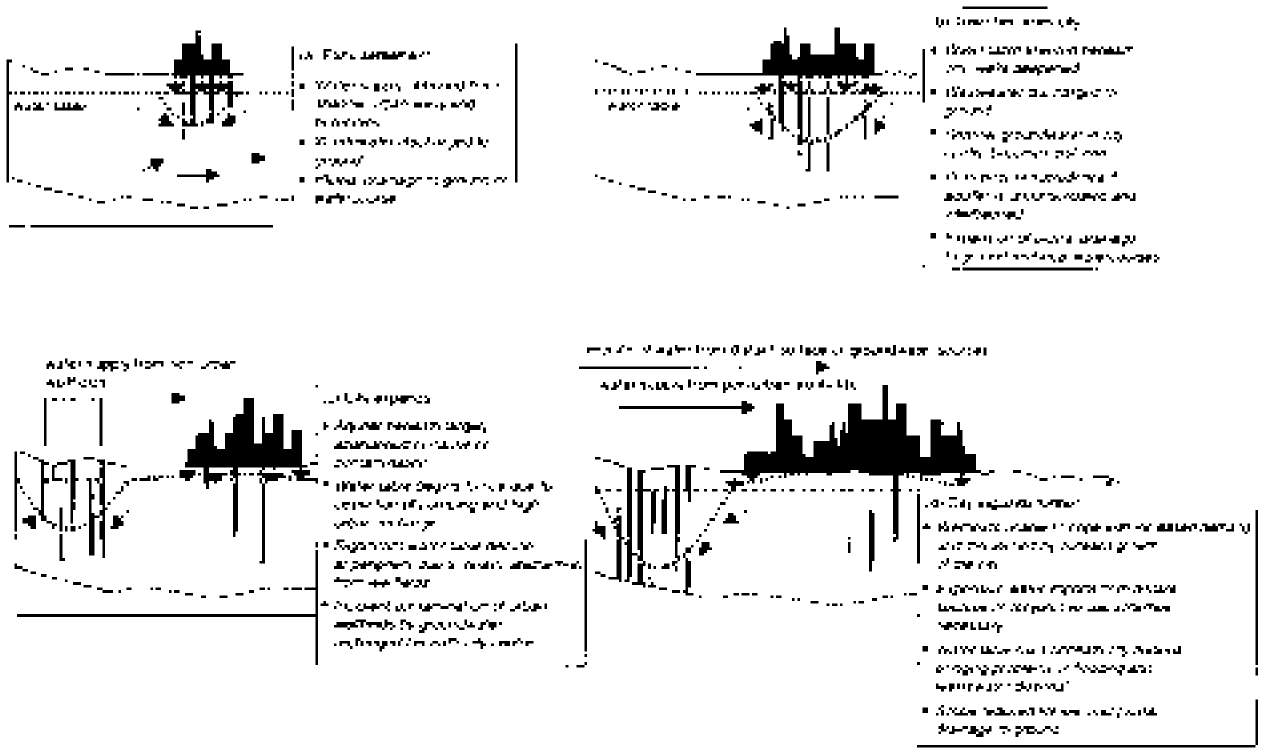

Figure 4. The role of groundwater during the evolution of a city (from Barrett, 2003, after Morris et al., 1997 and Foster et al., 1998).

Most mature cities eventually go into industrial decline and enter a post-industrial stage. The combination of declining industrial demand for groundwater with additional aquifer recharge, due to the leakage of imported water from reticulation systems, causes water levels to rise throughout central parts of the city. Pumping may be required to resolve the problem, but since the groundwater quality is poor, the well discharge must be directed to waste. Meanwhile, escalating demand for potable supplies means that water levels in peri-urban and rural areas remain seriously depressed. As observed by Barrett and Howard (2002), many of the problems reflect a lack of hydrogeological understanding and poor long-term planning. Most cities import, store and generate enormous amounts of potentially, water-contaminating chemicals (Figure 5), and the density of water quality monitoring wells is rarely sufficient to provide early detection of contaminants that migrate orders of magnitude more slowly in aquifers than they do in surface water courses. Volatile organic compounds from leaking underground storage tanks represent the greatest cause of groundwater quality degradation in the more prosperous cities, while faecal pathogens, nitrogen compounds (usually nitrate) and dissolved organic carbon (DOC) are the primary water quality concerns in cities of the developing world due to the close proximity between wastewater handling, disposal or reuse facilities and the underlying phreatic aquifer (Foster, 1990; Morris *et al.*, 1997) (Figure 6). Across the globe, widespread contamination of shallow urban groundwater (Howard and Gelo, 2002; Howard and Israfilov, 2002; Lerner, 2003) and subsequent under-utilization of the urban groundwater resource provide clear evidence of a failure in resource management (Barrett and Howard, 2002). As recognized by Morris *et al.* (2002), a particular problem in emerging nations is the ability to develop and enact management policies within the limited financial and institutional resources typically available to those responsible for planning and managing the urban water infrastructure.

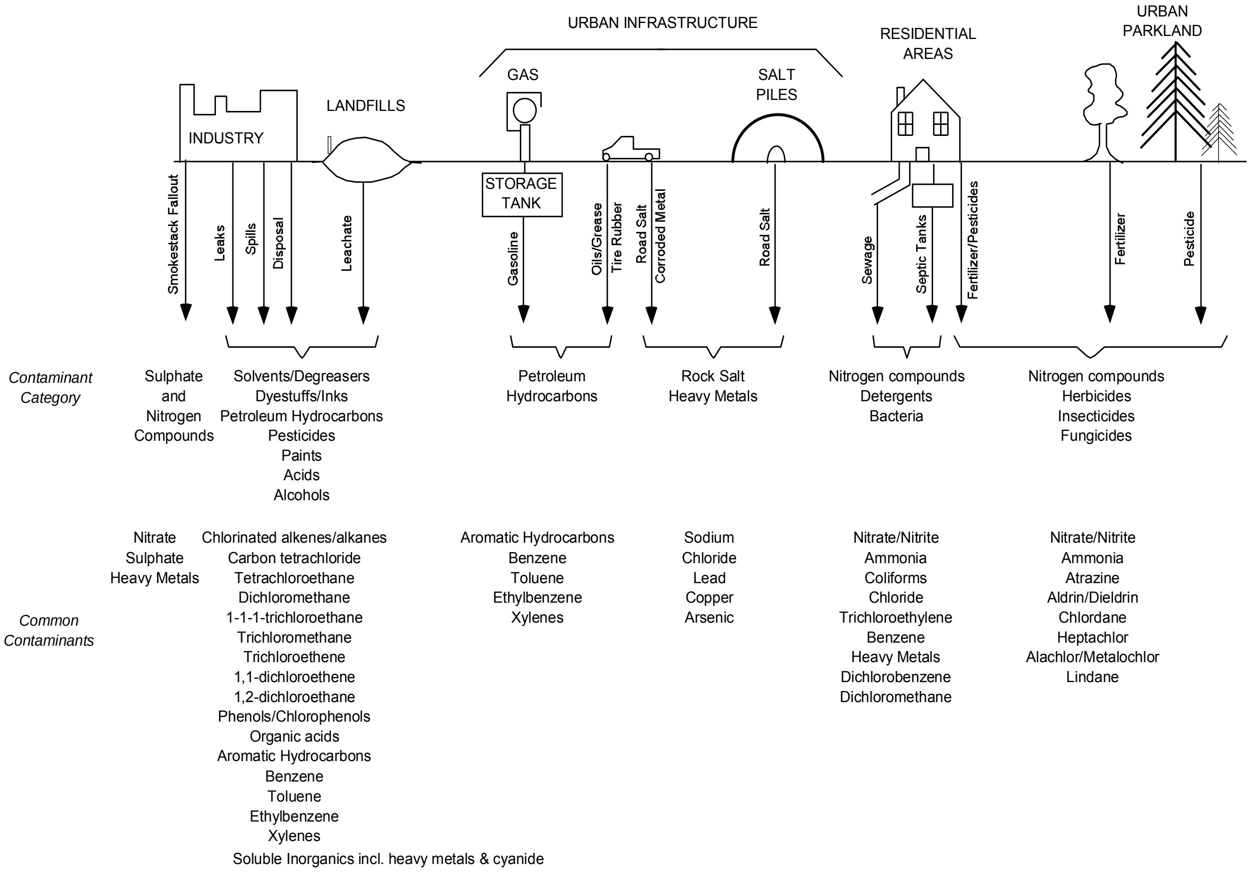

Figure 5. Sources of groundwater contamination in urban areas (from Howard, 1997).

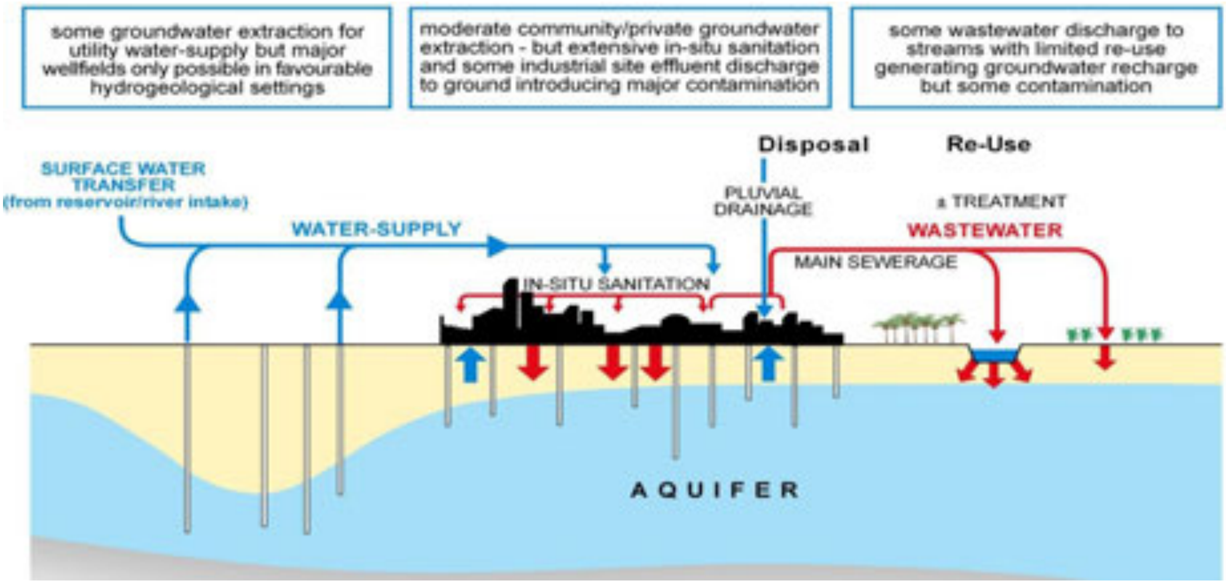

Figure 6. Unconfined groundwater and the man-made urban water cycle in developing cities.

Despite the enormity of the urban groundwater problem, there remain good reasons for cautious optimism. Issues related to urban groundwater are clearly complex, and the science of urban groundwater is extremely young when compared to its surface water counterpart. Nevertheless, much has been learned about the impacts of urban development on groundwater during the past 40 years, and that knowledge is gradually being incorporated into the urban planning and groundwater management process. For example, excellent progress has been made on:

- understanding the sources of urban recharge and quantifying components of the urban water balance;
- the development of novel techniques for augmenting aquifer recharge;
- pollutant source characterization, mechanisms of contaminant release and the behaviour of contaminant plumes;
- disposal methods for all types of domestic and industrial waste;
- approaches to monitoring;
- aquifer vulnerability mapping and methods of groundwater protection; and
- identifying opportunities for integrated / conjunctive use of ground and surface water sources.

In addition, there have been major advances in the development of computer model codes, many of which link seamlessly with urban database systems for the purposes of:

- performing urban water budget assessments;
- providing three-dimensional, transient simulations of the aquifer systems;
- identifying zones of contribution (ZOCs) – areas around production wells that require special attention in terms of aquifer protection;
- conducting aquifer susceptibility and vulnerability assessments;
- predicting groundwater travel times and eventual fate for contaminants in the system;
- determining "optimal" pumping and water extraction rates and, most importantly:
- testing and evaluating alternative water management scenarios, and thus supporting pro-active decision-making.

Some of these urban groundwater models (e.g. Pokrajac and Howard, 2011) acknowledge the importance of the entire urban water cycle and can simulate the interactions that take place between groundwater, surface water and the complex network of water services, including sewers and pressurized water supply systems.

In conclusion, the science is well advanced and the technology is strong. What is lacking is the structured framework of good governance that can fully exploit these major scientific and technical achievements. More importantly, governance structures are required that appropriately recognize the essential differences between groundwater and surface water, differences that can have very serious implications for water management policy.

2.3 Urban water issues at the rural-urban interface and peri-urban fringe

In recent years, an increased focus of attention on urban water issues related to urban population growth has drawn greater attention to areas at the urban-rural interface and within the peri-urban fringe, areas where much of the growth takes place. As a compounding issue, changing patterns of rural-urban integration in these areas (IFAD, 2001) provide an additional level of complexity to the water management problem.

Urban areas represent the engines of the world's economy, generating enormous benefits by concentrating human creativity and providing infrastructure and a workforce for intensive industrial and commercial activity. Urban growth brings new markets and increased human capital and opportunities for greater wealth and prosperity. Over the long term, cities will be the principal source of future economic development, but along with such promise comes immense challenges, notably in the form of concentrated poverty in largely peri-urban settlements characterized by squalid sub-standard housing with no security of tenure (i.e. "slums") (Black, 1994). Some peri-urban slums house as many as 70% of the city population.

Slums result from a noxious combination of weak governance, underinvestment in basic infrastructure, poor planning to accommodate growth, infrastructure standards that are unaffordable by the poor, and insufficient public transportation that limits access to employment. Left unaddressed, urban slums threaten both national and international security, human health and environmental sustainability. Most slum dwellers have low social status, low self-esteem and little or no representation and influence at levels of political power.

Peri-urban slums areas are frequently neglected by city planners. Most are unregulated and poorly serviced, and water quality degradation due to uncontrolled disposal of industrial, domestic and human waste is widespread. The majority of large cities enjoy the benefits of at least some water and sanitation infrastructure in their central areas, and in many cases, this is being improved and expanded by private companies or public utility commissions (PUCs), both of which can expect significant cost recoveries in the form of tariffs or taxes. Peri-urban slums seriously lack comparable infrastructure and services, and are frequently forced to use water sources that are unsafe, unreliable and sometimes difficult to access on a regular or continuous basis. Sanitation, where available, tends to be limited to latrines that are often shared with so many others that access and latrine cleanliness is difficult. Unsafe drinking water and inadequate sanitation have dire implications for human health, particularly the health of children and the elderly.

As a further complication, urban encroachment onto fertile agricultural areas inevitably leads to the decline and/or displacement of peri-urban farmers, who find that the scarcity of farmland is matched only by the scarcity of affordable freshwater for irrigation. In response, the peri-urban farmer often turns to urban wastewater (both treated and untreated) as the only reliable means of irrigating crops and maintaining a livelihood. Wastewater flows are typically more reliable than freshwater sources and are rich in the nutrients required for the cultivation of high-value crops. Unfortunately, the widespread use of wastewater has obvious implications for the edibility of crops sold at the market; moreover, the use of wastewater for irrigation seriously threatens the potable quality of shallow groundwater supplies. Authorities are also concerned that the seemingly beneficial, environmentally “green”, re-use of wastewater presents obstacles to installing wastewater treatment plants.

Assessing the risks associated with wastewater use is often difficult, as any enforcement of water quality standards is often complicated by ambiguous lines of authority; for example, should standards be enforced by health, agricultural or water supply and sanitation agencies? Consequently, its use is largely unregulated. A nationwide survey in Pakistan (WWAP, 2006) showed that approximately 25% of all vegetables are irrigated with untreated urban wastewater and that such vegetables, usually cultivated close to the urban markets, were considerably cheaper than the vegetables imported from more remote regions of Pakistan (Ensink *et al.*, 2004). Similarly, 60% of the vegetables consumed in Dakar, Senegal, are grown within the city limits using a blend of groundwater and untreated wastewater (Faruqui *et al.*, 2004).

2.4 The role of policy reforms

It would be remiss to evaluate global efforts to supply water to rapidly growing cities without considering the major reforms of water service that have taken place across the world during the past 20 years or more, primarily the result of various political and economic pressures. Prior to the 1990s, water industries in most countries operated as national monopolies. Since then, many countries have moved to introduce ‘decentralized’ systems of water service, often with varying degrees of success. For example, several Asian countries, including Indonesia, Pakistan and the Philippines, embarked upon radical decentralization programmes (WWAP, 2009) and, in many Latin American countries (e.g. Argentina, Chile, Colombia, Panama and Peru) national monopolies were sub-divided into hundreds of municipal providers as part of a wider process of devolution across all areas of government. Rapid decentralization also took place in Eastern Europe and Central Asia following the political turnaround that devolved responsibilities to lower tiers of government. However, the ‘purse strings’ have stayed mainly at the central level – a problem that is not uncommon for countries that choose to decentralize and devolve. In Africa, where only Tanzania and Ethiopia have chosen to decentralize rapidly, Ethiopia is running into problems because the transfer of important decision-making responsibilities to district and village levels has not been followed by the transfer of funds for capacity development.

In general, decentralization has not been a considered response to the specific water sector problems, but is more the consequence of wider national reforms. As a result, local governments often found themselves responsible for providing water service while lacking the capacity to deliver. Private sector involvement has had limited success. In larger urban centres, this has been primarily for political reasons, while in smaller cities and rural areas, economic viability is an additional problem. Thus, the real transition for most water consumers has not been from public to private, but rather from unregulated centralized public provision to regulated decentralized public provision. Today, most urban and peri-urban areas in the world are served by publicly owned and managed utilities, a model that is likely to continue (WWAP, 2009). In many developing countries, the performance of public utilities is often constrained by low motivation, poor management, inadequate cost recovery and political interference. The lack of public sector reform can be a serious obstacle to sustaining and increasing coverage and service. A particular challenge is to encourage public sector utilities to extend services to informal urban settlements (mostly slum areas) where cost recoveries tend to be low. Remarkably, good success can be achieved in such situations by partnering with local community groups or supporting private sector initiatives. For example, new contractual approaches have been developed in Paraguay, for example, to target the increased involvement of *aguateros* (mostly small-scale water companies), that have developed piped water supplies in peri-urban areas without public funding. These *aguateros* can now legally take part in public bidding processes, and their performance can be monitored, thus improving accountability.

2.5 IWM, IWRM, IUWM and the role of groundwater

Integrated Water Resources Management (IWRM) – together with its similarly motivated sister water management principles Integrated Water Management (IWM) and Integrated Urban Water Management (IUWM) – was first promoted by the United Nations in the 1950s. IWRM principles featured strongly at the United Nations Water Conference, held in Mar del Plata, Argentina, in March 1977, but the concept did not enjoy any serious traction until the 1990s when the principles of IWRM began to be endorsed by numerous international institutions.

IWRM is defined as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). Operationally, IWRM (and similar approaches) involves the application of knowledge from a range of disciplines, together with the insights from stakeholders, to develop and deliver efficient, equitable and sustainable solutions to the world's water problems. It can be described as a comprehensive tool for managing, developing and delivering water to consumers in a way that is socially, economically and environmentally responsible.

The IWRM model has enjoyed considerable acclaim. It has been adopted as a pre-requisite for compliance within the European Union's Water Framework Directive of 2000, and has provided guidance for subsequent EU water development programs such as the EU Water Initiative. Moreover, IWRM's open, multi-stakeholder approach to water management is undoubtedly the primary reason that the role of governance in water issues has achieved global attention. That said, IWRM is not a panacea for the world's water problems and has, from a purely practical standpoint, done little more than raise awareness for the complexity of urban water problems and point those responsible for solving such issues in more productive directions. While IWRM's primary attribute is its demand that global water issues be approached holistically, the number of factors that need to be considered and 'integrated' is so large that practical implementation is impossible unless the list is strongly redacted. Herein, serious problems arise. According to Biswas (2008), the application of IWRM to real world water projects has left much to be desired. At a scale of 1 to 100 (1 being no integrated water resources management and 100 being full integration), Biswas suggests that there is not a project in the world that would earn a score of 30 or more from an objective analyst.

In effect, the success of IWRM as a practical tool depends heavily on the factors selected for 'integration' i.e. which are listed and which are omitted. Since the term 'water' includes both ground and surface water sources by implication, it is generally assumed that groundwater and the role of aquifers are automatically included within IWRM's process of integration. In practice, nothing could be further from the truth. Debates on global water policy that rage at international water fora remain largely transfixed on surface water issues. For the most part, very little recognition or weight tends to be given to the vital function that groundwater plays in the global water cycle and the immense benefits that could be derived from the improved management of groundwater. A failure to recognize the unique and special attributes of groundwater represents one of the lost opportunities of IWRM.

2.6 Policy issues arising from current trends of urban groundwater use in developing cities

There is considerable evidence to suggest that dependence on groundwater for water-supply is increasing in developing cities (Foster *et al.*, 2011). This is occurring in response to:
- population growth;
- increasing per capita use;

- higher ambient temperatures; and
- reduced security of river-intake sources due to quality degradation and climate change.

The growth is facilitated by the generally modest cost of water wells and the fact that aquifers lie within a well's length of users (Foster *et al.*, 1998). It is estimated that over 1.5 billion urban dwellers worldwide currently rely on groundwater (Foster *et al.*, 2010b).

Where urban centres are underlain and/or surrounded by high-yielding aquifers, this has allowed water utilities to expand mains water-supply incrementally at modest capital cost — usually resulting in better mains water-service levels, lower water-supply prices and less private *in situ* use. However, there are rarely sufficient groundwater resources within urban areas themselves to satisfy municipal water-supply demands, and resource sustainability (both quantity and quality) often becomes an issue.

The growth in urban groundwater use is not restricted to cities with ready access to high-yielding aquifers (from which major utility water-supplies are drawn), but also widely occurs where the utility water-supply is imported from considerable distance (usually from a surface water source). In such cases, private *in situ* water-well construction has often flourished due to inadequate (present or historic) municipal water-service levels and/or high water prices. For example (Foster *et al.*, 2010b):

- in Brazil many cities experienced major private water-well drilling 15–20 years ago, in response to water-supply crises during extended drought, but such water wells continue because they provide a lower-cost water supply.
- in Sub-Saharan Africa, despite much higher unit costs of drilling, water wells (for direct water collection or reticulation to standpipes) are widely the fastest growing source of urban water supply in the struggle to meet escalating demand.
- in Peninsular India, water-well use for urban residential self-supply is ubiquitous in the face of very poor utility water services (often 1-in-24 hours or less) and greatly reduces dependence on expensive tankered water supplies.

In terms of water management policy, an immediate issue concerns the relative benefits and risks of in-situ residential use (Table 3) and how this can be regulated given that many wells are technically illegal. In the

Table 3. Advantages and disadvantages, from a public administration perspective, of urban private, in-situ residential water supply from groundwater (Foster et al., 2011)

Pros	Contras
Greatly improves access and reduces costs for some groups of users (but not directly for the poorest because without help they cannot generally afford the cost of water-well construction).	Interactions with *in situ* sanitation can cause a public-health hazard and could make any waterborne epidemic more difficult to control.
Especially appropriate for 'non quality-sensitive' uses—could be stimulated in this regard to reduce pressure on stretched municipal water supplies.	May encounter sustainability problems in cities or towns where principal aquifer is significantly confined and/or mains water- supply leakage is relatively low.
Reduces pressure on municipal water-utility supply and can be used to meet demands whose location or temporal peaks present difficulty.	Can distort the technical and economic basis for municipal water- utility operations, with major implications for utility finance, tariffs and investments.
Incidentally can recover a significant proportion of mains water-supply leakage.	

developing world, *in situ* private self-supply from groundwater widely represents a significant proportion of water actually received by users (Foster *et al.*, 2011), and its presence, while impossible to quantify reliably, has major implications for municipal water utilities. The initial motivation for the private capital investment in self-supply is usually triggered during periods of partial failure or highly inadequate municipal water-supply service — essentially as a coping strategy. However, continued use is essentially a cost-reduction strategy, since the actual (or perceived) cost of in situ groundwater is lower than that of the applicable municipal water-supply tariff. In some cases, the initial investment itself is justified by cost reduction, where water-well capital costs are modest when compared to cumulative municipal water-supply tariffs.

Table 4. Summary of major policy issues related to urban municipal groundwater use (from Foster et al., 2011)

Issue	Implications
Municipal water-supply benefits and risks	Groundwater use for municipal water supply has many benefits (including capacity to phase investments with growth in demand and high quality, requiring minimal treatment), but it comes with a need for integrated planning of urban land use, effluent discharges and solid-waste disposal to avoid insidious and near-irreversible pollution.
Protected municipal well fields	Since some degradation of groundwater quality in urban municipal water-wells due to persistent pollutants is likely, it is necessary, in parallel, to develop 'external well fields' and declare their capture areas as 'protected zones' to guarantee that a proportion of the total resource is of high quality and available for dilution or substitution, and keep them protected as urban area expands
Conjunctive use with surface water	The rates of replenishment of aquifers may not be sufficient to meet the demands of larger cities sustainably and in this situation it is preferable to use available groundwater resources and large storage reserves conjunctively with surface-water sources, thereby conserving groundwater for use during drought and other emergencies.
Future drainage problems	Avoiding radical reductions in municipal water-well use (due to an increased offer of subsidized mains water supply or to quality deterioration/pollution rumours) with water-table rebound (to higher than the pre-urbanization condition), which could result in potentially serious sanitary problems and infrastructure damage in lower-lying areas.

The other major policy issues relate to municipal groundwater use (Table 4). They include (Foster *et al.*, 2011):

1) Integrating groundwater into infrastructure decision-making

   A more integrated approach to municipal water-services and urban development is required to avoid persistent and costly problems – and this must include consideration of groundwater sustainability, especially where local aquifers are providing an important component of municipal water-supply. In developing cities, a frequent concern is that too much public water-supply abstraction is concentrated within urban municipal limits, leading to deep unstable cones of piezometric depression and causing secondary problems (e.g. induced pollution of contaminated surface water, saline-water intrusion and land subsidence). Given the dynamic nature of groundwater in urban areas, it is appropriate to take an adaptive approach to resource management that is guided by predictive groundwater flow models and fine-tuned on the basis of data continuously collected from a network of monitoring wells (water levels and water quality). In the long term, sustainable municipal water supply solutions will likely involve:

   - the conjunctive use of groundwater and surface water resources (Paling, 1984);
   - aquifer recharge enhancement using storm water infiltration techniques (Ward and Dillon, 2011) designed to minimise groundwater pollution risk; and
   - greater efforts to reduce distribution losses

   An adaptive management approach (NRC, 2004; Gleeson *et al.*, 2012) is essential, as the predicted impacts of pumping are never completely reliable, and management plans will always require at least minor refinement. A particular concern in urban areas is that relatively small operational changes in the well field may lead to water-table rebound and the risk of damage to urban infrastructure and sanitation systems.

2) Proactive land-use management to reduce groundwater pollution threats

   To control or reduce the pollution threat to municipal water-wells, it is essential to take a proactive approach on urban land use involving:
   - prioritizing recently urbanised areas for coverage by mains sewerage or limiting density of new urbanisations with in-situ sanitation to contain nitrate contamination to tolerable levels;

- establishing municipal water-well protection/exclusion zones around any municipal sources that are favourably located to take advantage of parkland or low-density housing areas;
- using groundwater pollution hazard assessments to identify municipal water-wells with an especially high risk of contamination from toxic synthetic organic substances; and
- avoiding the creation of 'upstream' polluting discharges and making the best 'downstream' use of wastewater without compromising groundwater quality in existing municipal water-wells and well-fields (Foster and Chilton 2004).

3) Development of protected 'external' municipal well-fields

   Cities dependent upon groundwater for municipal water supply widely encounter problems of increasing and/or elevated concentrations of residual persistent urban contaminants (notably nitrate). The most cost-effective way of dealing with this type of problem is by dilution through mixing (i.e. blending), which requires a secure and stable source of high-quality supply such as that produced from a suitably located and carefully protected 'external well-field'.

   In the developing world, the promotion of external well-fields often encounters impediments related to fragmented administrative powers for land-use and pollution control between the major actors. The problem is especially difficult where the needs of a growing urban area conflict strongly with agricultural interests. There are no established procedures or incentives for the resource interests of an urban municipality to be assumed and maintained by a neighbouring rural municipality, such that adequate protection can be offered for the capture area of the external well field.

Clearly, solutions are available to deal with important planning issues as they relate to groundwater. The overriding challenge is to provide a framework for water governance in urban areas that can facilitate action on these solutions. For example (Foster *et al.*, 2010a):

- in urban environs land-use classification and control are generally the domain of municipal or local government, and the absence of mechanisms whereby water resource agencies can influence the process is a frequent governance weakness.
- in many developing countries, legislation to cope with undesirable land-use practices is often weakly enforced or even non-existent and progress with implementing controls in the interest of groundwater are highly dependent upon stakeholder awareness and participation.

In Chapter 3 (the Thematic Diagnostic – below) we conduct a more detailed analysis of governance issues by reviewing water-related problems in cities where groundwater plays a major role. The findings of this analysis are carried through to Chapter 4 where appropriate models of urban water governance are identified and discussed.

3 Thematic Diagnostic

The purpose of this chapter is to provide a closer examination of how water governance (or the lack of it) influences the management of groundwater in and around cities. Recognizing that a complete and thorough review of the all the world's cities lies well beyond the scope of this paper, preference is given to cities that can provide insight to the types of urban groundwater issues that commonly lead to tensions and conflict. In total nine cities are considered. They include Mexico City (3.1), Ta'izz (Yemen) (3.2), Delhi (3.3), Chennai (formerly Madras) (3.4), Fortaleza (Brazil) (3.5) and Cochabamba, Bolivia (3.8) – where groundwater problems remain largely unresolved – and Narayanganj (Bangladesh), Bishkek (Kyrghyzstan) (3.6) and Bangkok (3.7) – where important progress is being made. The various successes and failures provide a valuable insight to the opportunities for urban groundwater management and how good governance can be achieved. A particular feature of these case studies is that they illustrate the human dimension of the management problem and the role individual consumers can and must play in the pursuit of sustainable solutions.

3.1 Mexico City

The Mexico City Metropolitan Area (MCMA) (pop. 21,2 million) enjoys one of the highest coverage levels of water supply and sewerage in the country (Castro, 2006). The average Mexico City resident uses 300 litres of water each day which far exceeds the internationally accepted standard of 100 litres to cover essential household needs. Despite calls for demand management, water remains highly subsidized with only 5% of the water supply cost recovered (Castelan, 2001). In reality, the 300-litre "average" likely includes the 30-40% of this water that is 'lost" via leaky reticulation systems. It also conceals the fact that individual use varies from as much as 600 litres per day in richer parts of the city, to just 20 litres per day in poor areas. Since the 1980s, the MCMA and surrounding areas have seen recurrent social conflicts sparked by water service issues. Problems in the region include groundwater overexploitation, land subsidence, the risk of major flooding, poor water quality, inefficient water use, very limited wastewater treatment, and health concerns about the reuse of untreated wastewater in agriculture.

Reliable data are difficult to obtain. However, the MCMA appears to derive around 70% of its water from the severely over-exploited local aquifer system (over 45 m^3/s pumped for municipal use compared to a natural recharge of about 20-25 m^3/s). The remaining water needs are imported. Around 15 m^3/s are obtained from the Cutzamala river basin to the west, a transfer that is energy-intensive as it requires a vertical lift of over a 1000 m. A very important issue that had not been resolved concerns the compensation of communities that were resettled due to the construction of the Cutzamala project (Tortajada, 2006). Just as contentious is the 6 m^3/s of groundwater that is imported from the Lerma basin, a distance of about 60 km to the west of the city. The project began in 1942 with delivery of 4 m^3/s and this was increased to 14 m^3/s between 1965 and 1975. The supply was scaled back to 6 m^3/s due to environmental impacts and social conflicts. Overexploitation of the aquifers in the Lerma area reduced the fertility of the soils, and many lands supporting irrigated crops were reverted to rain-fed agriculture with little consideration of compensation to farmers. More recently, a newly planned diversion of water from the Temascaltepec basin (5 m^3/s) has stalled (Molle and Berkoff, 2006) due to fierce resistance from farmers who fear that tunnel construction will dry up springs (El Naranjo, La Huerta, El Sombrero and El Chilar) and affect agricultural production (predominantly maize, sugar cane, banana, tomato, melon and peas).

The challenges for Mexico City remain enormous, as serious interruptions in water supply would be viewed as a national crisis that could readily destabilize the Federal Government. Overcoming these challenges is made particularly difficult by the highly fragmented institutional arrangements for water management with various, and sometimes overlapping, responsibilities distributed across all levels of government. These include:

1) the Federal Government and its National Water Commission (CNA, *Comisión Nacional del Agua*) which is responsible for regulating the use of water resources, financial investment and the import of bulk water from neighbouring basins;
2) the State of Mexico, which supplies bulk water, treats wastewater and assists municipalities with water and sanitation services in the part of Greater Mexico City that lies within the State of Mexico;
3) 59 municipal governments and one municipality in Hidalgo State individually responsible for supplying water distribution and sanitation services to their local constituents;

4) the water department of the MCMA's Federal District which is in charge of water distribution and sanitation for its local jurisdiction; and
5) two irrigation districts in Hidalgo state who take responsibility for irrigation using the city's wastewater.

In 2007, the Federal Government, the State of Mexico and the Federal District attempted to overcome these institutional barriers to effective water management by launching a US $2,8 billion Water Sustainability Programme. The aims of this programme were to minimise the risk of major floods, treat all collected wastewater and reduce groundwater overdraft. At the same time, the government of the Federal District launched a 15-year "Green Plan" with water conservation as its central theme. The plan included measures to increase aquifer recharge through land use controls and recharge wells, the construction of tertiary wastewater treatment plants that would allow treated wastewater to be used for aquifer replenishment, eradication of illegal connections and the installation of water meters that would ensure all users paid for the water they used. While these measures were expected to reduce groundwater abstraction in Greater Mexico by 10% and the overdraft by 25%, additional measures would be required to balance abstraction with aquifer recharge.
Any hope that the water situation will improve for the city of Mexico seems to be stifled by Jordan *et al.* (2010), who suggest that the complex administrative structure with competing jurisdictional interests remains a major obstacle towards any significant progress.

3.2 Rural-urban transfers of groundwater in Ta'izz Region, Republic of Yemen

Yemen (pop. 24.3 million) is the poorest country in the Middle East with a 35% employment rate and dwindling natural resources. The modern Republic of Yemen formed in 1990 when traditionalist Islamic North Yemen and Marxist South Yemen merged after years of cross-border conflict. However, serious tensions remain with southerners complaining that northern part of the state is economically privileged. Widespread corruption is a major obstacle to development in the country, limiting local reinvestments and driving away regional and international capital.

With renewable water resources of only 125 cubic meters per capita/year Yemen is one of the most water-scarce countries in the world. Today, there are probably as many as 70 000 wells in Yemen, the majority of which were drilled without license and are under private control. Since 90% of water withdrawals are used for agriculture, issues related to land and groundwater governance are a common source of conflict. Inadequate legislation and ineffective institutions heighten the problem. According to the Yemeni Constitution, surface and groundwater resources are communal property, which is consistent with customary Islamic principles of water management.

Ta'izz (pop. 600 000) is a city in the Yemeni Highlands, lying at an elevation of about 1 400 metres above sea level. After the capital Sana'a and the southern port of Aden, it is the third largest city in Yemen, and like most Yemeni cities it has a highly unreliable water supply. Increasing numbers of people have to rely on more costly water supplied by rural private wells and imported by water tanker. The quality of this water is questionable because the tankers are used for many other purposes.

During the late 1990's efforts have been made by the National Water Resources Authority (NWRA) to improve the water supply for Ta'izz by implementing a system of water transfers from rural to urban communities. Key features of this system included both demand management measures (such as input taxation and public education campaigns) and social measures (through a regime of tradable water rights). The water transfer system was developed over a period of several years in close consultation (and often in heated debate) with the local rural communities, particularly farmers, who traditionally have little faith in government institutions. The process was considered as a valuable opportunity for confidence-building and special efforts were made to avoid any breakdown in the dialogue. As an end result, the communities agreed that rural-urban transfers should proceed according to the following key principles (WWAP, 2003):

- there should be clearly defined rights, taking into account ethical considerations such as priority for drinking water needs.
- except for water needed for drinking and basic needs, water should be allocated through market-like processes. Water rights should be tradable and, to the extent possible, there should be direct compensation for individuals willing to transfer their water rights to others, which is commensurate with the rights transferred.

- water transfers should be verifiable. Those who agree to transfer their water rights must reduce their water use accordingly.
- the local communities should participate in designing the rules and mechanisms to govern rural-urban transfers, including a mechanism for monitoring compliance and punishing violators.
- NWRA should have an oversight role in rural-urban transfers to ensure resource sustainability and equity.

3.3 Access to potable water supplies in the National Capital Territory of Delhi, India

Most cities in India face a severe scarcity of water, a problem that is seriously compounded by population growth. Much of the growth takes place in peri-urban areas, where land is rapidly consumed by unplanned urban housing, industrial premises and disposal sites for urban waste (both solid and liquid). Very little effort is made to provide basic water services to these areas and this frequently results in unplanned and unregulated exploitation of groundwater, mostly by private operators (Janakaranjan, 2005). In many respects, the problems are more severe in the cities sited on the low-storage hard-rock aquifers of Peninsular India than they are in cities and large towns on the Indo-Gangetic floodplains. For example, Lucknow City (pop. 2,9 million) is situated on the Central Ganga alluvial plain, and has access to thick, productive alluvial sand aquifers such that water scarcity is more related to the city's ageing, leaking and regionally inefficient water distribution system than it is by resource availability constraints (Foster and Choudhary, 2009).

In the National Capital Territory of Delhi (NCT), (pop. 16,7 million) the water supply is erratic, unequally distributed and well below international standards. In Delhi, the public undertaking (the Delhi Jal Board, DJB) is simply unable to meet the city's water and wastewater needs (Janakaranjan *et al.*, 2006). The mismanagement of water particularly affects the urban poor in city slums where supplies average 27 litres per person per day (Llorente, 2002). In response, the city has seen a rapid rise in the use of low-cost water wells for residential self-supply as an essential "coping strategy" that greatly reduces dependence on expensive tanker supplies (Foster *et al.*, 2011). As a consequence, aquifers are becoming depleted due to increasing demand.

In Delhi, as throughout India, the natural response to rationed water supply, an inefficient delivery of municipal services and lax regulations has been for users to develop compensatory strategies. These strategies are described as "decentralised governance structures" and can be formal or informal. With formal strategies, private operators sell water via water tankers. The absence of regulation means that the source of this water cannot be guaranteed with some opportunistic companies reselling public water or untreated groundwater from illegal wells. More reputable private operators support better regulations but have received little support from the government. They struggle to provide services, which are both reliable and affordable. Informal structures are developed by the poor and rich alike. The poor are more likely to take a 'free-ride' on the public network via illegal connections, while higher income households will often install devices to store water in roof-top tanks and install tube wells for *in situ* supply. Neither the formal nor the informal strategies can be considered socially, economically and environmentally sustainable.

All these decentralized solutions have a fairly high cost, despite water being apparently free. One of the solutions mentioned concerns the institutionalization of community participation mechanisms that are good for at least three reasons: it would enable these costs to become endogenous and facilitate the organization of a system of transparent redistribution; the residents would actually be able to ensure the up-keep of the decentralized installations; it would facilitate more effective management of the resource through the detection of leaks and better management of the demand. The rights of access would be ensured. This requires considerable institutional improvements in the different localities studied, and in particular the setting up of mechanisms for consultation, negotiation and above all of regulation.

Janakaranjan *et al.* (2006) recommend that the first goal should be the simplification of the institutional framework by redefining responsibilities in order to better coordinate the various decision levels, avoid the overlapping of tasks and limit the intervention capacity of discretionary powers. The second goal stresses the concept of a democratic decision-making process in which all the interest groups in the system would be represented (from the infra-local level to the whole area), which would act like a broad-based regulatory framework. Lastly, the third proposition considers it essential to redefine the constituents of the public service and its articulation in operational terms. It especially implies a reversal of the perspective, in the sense that the service should not be conceived in a technocratic top-down manner by imposing arbitrary norms, but in terms of the fundamental needs that should be met, taking into account the different systemic effects.

3.4 Growing conflicts with peri-urban users in Chennai (formerly Madras), India

The city of Chennai is one of the more seriously afflicted cities in India (Janakaranjan, 2005), with the Chennai Metropolitan Water Supply and Sewerage Board (Metro Water Board or MWB), supplying less than 50% of the population's need. As in most Indian cities, groundwater plays a crucial role in filling the demand gap (Zérah, 2000). Unfortunately, the city's groundwater resources are seriously depleted. In some areas, water levels are so low that intrusion of seawater has occurred. Immediately north of the city, the seawater extends 16 km inland from the coast. To date, there has been no solution to the water supply crisis in Chennai. Possible megaprojects (involving major inter-basin transfers) have been rejected due to cost.

For the past two decades, the MWB has relied heavily on the transport of water from public wells and agricultural wells located in peri-urban villages. The present supply to Chennai is about 103 million litres per day which is pumped from city boreholes, the Poondi, Tamarapakka, Flood Plains, Kannigaiper and Panjetty well-fields located to the northwest just beyond the Chennai Metropolitan area, and the Minjur and Southern Coastal Aquifer well-fields that lie within the Metropolitan area to the north and south of the city of Chennai, respectively. Importing groundwater from peri-urban areas can create various types of tension (Janakaranjan *et al.*, 2006):

1. Impact on poverty and livelihoods. Groundwater extraction from common lands in per-urban villages is not new. In 1969, the MWB dug 10 wells in the common lands of a nearby village to solve a water crisis in Chennai and transported water through pipelines. The MWB also demanded that farmers in many of the villages sell the water pumped from their irrigation wells, and many agreed. A study carried out by Gambiez and Lacour (2003) showed that farmers fell into three groups:

   A) those who refuse to sell water to the MWB;
   B) those who own wells and sell their water to the MWB; and
   C) those who do not own wells and need to buy water from the first group to irrigate their fields.

   An analysis of these groups showed that group A suffered a slight loss of income due to a reduction in cultivated area, presumably a direct influence of peri-urban population growth and the transformation of rural land to urban. By comparison, groups B and C were markedly affected. Between 2000 and 2001, farmers contracting with the MWB (Group B) reduced their cultivated area by 43 per cent, while increasing their revenue for the period 1999-2002 by 80%, the water sales business proving considerably more lucrative than farming. Dependent farmers (Group C) were the losers, seeing a considerable reduction in both irrigated land and farming income. This illustrates how a simple arrangement, initiated by a public undertaking, can create problems with severe social and economic implications.

2. Tensions over the lax regulatory framework. By the mid-1980s, when Chennai's available sources of water supply began to decline, the Chennai Metropolitan Area Ground Water (Regulation) Act was passed that enabled the MWB to grant or deny permits to construct wells in designated areas and to grant or deny licenses for extraction, use or transport of groundwater. The purpose of the act was to ensure that groundwater be used exclusively for domestic needs and prevent the common practice of transporting groundwater by trailer, lorry or similar goods vehicles. Two decades later, the MWB has been the main violator of the legislation, causing much of the groundwater overdraft in peri-urban villages that the Act was designed to prevent. The MWB continues to draw groundwater from the designated areas, expanding its "catchment area" to peri-urban areas as much as 50 km beyond city limits. It also operates lorry-tankers without license. Many private lorry-tankers also transport groundwater from remote peri-urban areas, mostly to industry, many operators complaining that their permit applications have been ignored. In terms of permits to sink new wells, the legislation is also widely disregarded. Many industries draw water in contravention of the Act; they are also a major cause of water quality degradation. However, as is common throughout India, enforcement remains a major issue, and there is no evidence to indicate that the MWB has prosecuted any industry for violating regulations.

Finding solutions to the Chennai water supply problems will be difficult. However, there has been some success in creating a meaningful dialogue on the issue through a multi-stakeholders platform (MSP) designed to generate multi-stakeholder dialogue (MSD). For Chennai, a 65-member multi-stakeholder committee was initially established compromising water users from both urban and per-urban areas. It included farmers (both water sellers and non-water sellers), landless agricultural labourers, women self-help groups, NGOs, researchers, lawyers, urban water consumers and a few government officials. More members were added at subsequent committee meetings. The MSD process has addressed several key issues including declining groundwater levels, declining agricultural activities, emerging livelihood problems, seawater intrusion, deteriorating water quality, water and soil pollution, sand mining and people's growing unrest. The challenge will be to secure the cooperation of the MWB and similar government agencies in getting potential solutions implemented.

3.5 Groundwater use in metropolitan Fortaleza, Brazil

In 1950, 37% of Brazilians lived in urban areas (19 million urban dwellers). By 2000, the urban population had risen to 137 million representing 81% of the total. With a population close to 2,3 million (the metropolitan region is currently over 3,4 million), Fortaleza is the 5th largest city in Brazil and one of Latin America's fastest growing cities. CAGECE (Companhia de Agua e Esgoto do Ceará) is responsible for the city's mains water supply and provides service to 60-70% of the population using surface water. This service is unreliable during periods of peak demand and almost fails completely during periods of drought. According to Foster and Garduño (2006), this has prompted a remarkable 40-60% of the population to seek supplementary water supplies in the form of *in situ* water wells. This practice is common for multi-residential properties but is also popular for single occupancy dwellings. Groundwater is also a popular choice for the manufacturing, recreation and tourism sectors. A 2002-03 water well inventory documented almost 10 000 wells, a six-fold increase over 1980. On the downside, reconnaissance sampling showed water quality problems in over 70% of the wells. The primary problems included NO_3 and NH_4 related to waste water discharge from unsewered sanitation and elevated salinity due to seawater intrusion. Also a significant number of the larger users (over 2 m^3/hour) were found to be operating without permits. The authors recommended that water supply provision and sanitation/drainage infrastructure of Fortaleza be analysed to assess the current influence of groundwater self-supply, together with associated potential future opportunities and risks. They also identified the need to stimulate high-level discussion and policy-decision on groundwater issues as they relate to urban infrastructure planning in Fortaleza, and on a proactive management campaign with institutional roles clearly defined for the various actors.

3.6 Approaches to aquifer protection plan development in Narayanganj, Bangladesh, and Bishkek, Kyrghyzstan

The pollution of shallow groundwater by human, domestic and industrial waste represents one of the most serious constraints on groundwater utilisation in rapidly urbanising areas. Yet, very few cities outside the high-income world have developed and implemented strategies for protecting groundwater as integral parts of their groundwater management plans. Morris *et al.* (2000, 2002 and 2005) present two examples of cities where, despite a limited resource and knowledge base, locally appropriate and hydrogeologically sound groundwater protection plans have been successfully developed following close consultation with local stakeholders. The cities are Narayanganj, Bangladesh, and Bishkek, Kyrghyzstan.

Narayanganj (pop. 2,9 million) is located on the flat Ganges-Brahmaputra-Megna alluvial plain of central Bangladesh. Long known for its jute industry, the city has become an important textile manufacturing centre in addition to its expanding soap-making, metal re-rolling and metal and wood furniture manufacturing industries. It depends 90% on groundwater for supply but has no wastewater disposal system, relying on dispersed on-site sanitation in urban, peri-urban and rural areas. The city is fast becoming an industrial satellite suburb of Dhaka, a megacity centred 20 km to the north-west which is undergoing rapid, unchecked growth.

Bishkek (pop. 850 000) is Kyrghyzstan's industrial centre and is 100% aquifer-dependent for potable, domestic, commercial and industrial water supplies which are provided by both intra-urban and peri-urban well fields. The city lies on the outermost northern flanks of the foothills of the Alatau range of the Tien Shan Mountains, at an elevation of 725-900 m above sea level. The wastewater disposal system includes mains sewers for industrial, commercial, apartment and public buildings, and dispersed on-site sanitation for many low-rise residential areas. The relative importance and geographical extent of the latter is not well documented, but may be significant. A wastewater treatment plant for domestic and industrial effluent is located to the north of Bishkek.

Commencing in 1998, aquifer protection plans were developed for the cities using a very similar approach. The work began with aquifer vulnerability and subsurface contaminant load surveys to provide pollution risk assessments (Calow *et al.*, 1999; Morris *et al.*, 2002). Data for these assessments were sought from as many information sources as possible (Table 5) including and thereby involving, where possible, national agencies. The second and arguably most important stage was to engage groundwater stakeholders in the development of the groundwater protection plan. This plan involved a concise set of policy guidelines and a groundwater resource planning map. The overall purpose of this novel collaborative approach was to engender a greater ownership of the groundwater protection policies and thereby make them enforceable.

Table 5. Pollution risk assessment information sources (modified after Morris et al., 2002)

Organization/Agency	Narayanganj	Bishkek
Municipal Water Supply Utility	√√	√
State Geological/Hydrogeological Survey	5	√√
State Water Resources Agency	√	√
National Environment Agency	5	5
National Map Survey Department	5	5
National Government Census/Statistic Agencies	√	√
Other State Ministries/Departments/Agencies	√	5
National/Municipal Public Health Department	√	√
University or Other Water Research Institute	√	√√
Municipal Planning/Public Works Departments	5	5
Chamber of Commerce/Trade Organization	5	5
Consultants' Reports	5	5
Commercial Directories/Institutions	√	√√
External Support Agencies e.g. UNDP	√	5

Key: √√ Important source of data; √ provided some data; 5 unable to provide relevant data/not available

Key to the identification of stakeholders in Bishkek and Narayanganj was a clear understanding of each city's groundwater development setting and urban water infrastructure. These were quite different in each city. For example, in Narayanganj:

- industrial users are important and influential stakeholders, meriting extra effort in consultation.
- there is overlap between rural and urban water supply agencies, especially in the peri-urban area.
- users of the shallow aquifer, which still serves as a resource as well as a receptor proved difficult to represent.
- no primary stakeholder groups could be identified.

By comparison, in Bishkek:

- state sector agencies remain the predominant stakeholder group members.
- only secondary stakeholders could be identified.
- a post-independence depression in industrial activity offered opportunities for context-sensitive planning intervention to support a sound basic infrastructure.
- although the upper aquifer is not widely used for potable supply, hydrogeological conditions indicate the potential for rapid vertical movement of pollutants to deeper supply aquifers.

In both cities, it proved impossible to identify representative primary stakeholders (those with a direct resource interest, including groundwater users) who could participate in a consultation process. Although participation by primary stakeholders was considered desirable, it was recognized that such user groups, sufficiently organized (and thus representative) will be found only in some urban contexts. In Narayanganj the absence of this stakeholder class was more than compensated for by the diversity of secondary stakeholders (intermediaries in the delivering of policies, projects and services to primary stakeholders). These were drawn not only from public sector agencies/ministries but also local government and trade/industry associations. In Bishkek, public sector organizations dominated the stakeholder spectrum but – presumably as a result of underfunding and poor coordination post-independence – proffered a diversity of views and were actively engaged in the discussion of options.

3.7 Successful control of groundwater production in Bangkok, Thailand

Buapeng and Foster (2008) report on a progressive, adaptive, and eventually successful, control of groundwater abstraction in Greater Bangkok, in the face of serious environmental degradation. It demonstrates how consistent and persistent application of regulatory measures (licensing and charging) targeted in objectively-defined priority areas can reverse trends in groundwater resource decline and environmental degradation with minimal discontent amongst users.

Greater Bangkok (pop. 12 million) is underlain by 500-m-thick accumulation of alluvial and marine sediments that support a very productive multi-level aquifer system. The uppermost clay, which confines and helps protect the aquifer system throughout much of the urban area, thins out north of the city where most of the recharge occurs. Widespread exploitation of groundwater for urban water-supply commenced in the 1950s and this led to land subsidence of over 60 cm in the centre of the city by the mid-1980s. The subsidence caused substantial damage to the urban infrastructure and exposed the city to a high risk of flooding during tidal surges. In addition, the lowering of the potentiometric level to below mean sea-level significantly raised the threat of groundwater quality degradation due to the intrusion of seawater.

In response to the growing problems, the public water authority progressively closed its pumping wells beginning in 1985. However, although production was eliminated by the late 1990s, increased domestic, commercial and industrial tariffs for mains water-supply (imported from distant sources) triggered a massive increase in the drilling of private water-wells for:

- domestic and low-demand commercial users requiring wells about 150 m deep to supply around 1 Ml/d;
- industrial users requiring expensive 500 m deep wells to produce up to 10 Ml/d.

Faced with deteriorating environmental problems, the government increased its efforts to control pumping by:

- defining ‘critical areas’ where water well drilling would be banned;
- adopting the power to seal water wells in areas with mains water-supply coverage; and
- licensing and charging for groundwater according to metered (or estimated) abstraction rates.

Initially, pricing was set at nominal levels that provided little incentive to reduce pumping but did, at least, establish the administrative framework and provide a useful database. Subsequently, charges were increased and structured to ensure that the greatest financial burden was borne by industrial and commercial users in ‘critical areas’. Public awareness campaigns were introduced and the well sealing program was aggressively pursued. Slowly, the situation was brought under control.

By 2008, there were just over 4 000 licensed water-wells in Greater Bangkok providing about 15% of the total water supply. Licenses are required for all wells more than 15 m depth (i.e. exploit the main freshwater aquifers). Around 58% of the current licensed production is for industrial use. Many of the largest industrial water-users have been driven out of Greater Bangkok by the high water charges. The other primary user group includes private urbanizations/large apartment blocks that do not have access to mains water-supply. Conflicts arose in some districts when an extension of the mains water-supply resulted in substantially higher costs for water. The dispute was resolved by allowing water-well users to continue using their wells conjunctively for the duration of their present licence, and to retain their wells as a back-up supply for 15 years, provided they were adequately metered and open to inspection.

One groundwater management aspect, which remains outstanding, concerns groundwater pollution control in the recharge area to the north of Bangkok. While the local regulatory agency has the responsibility and capability to identify areas of higher vulnerability that lie within the capture zones of municipal wells, it has no jurisdiction over activities that are potentially polluting, e.g. the storage and handling of industrial chemicals, effluent discharge to the ground and agricultural practices. This urban-rural ”co-management” issue clearly needs to be resolved.

3.8 A cautionary tale of water privatization in Cochabamba, Bolivia

Cochabamba, Bolivia, is a thirsty, sprawling city of an urban population of over 600 000, and a metropolitan population exceeding 1 million. The fourth largest city in Bolivia, its population quadrupled towards the close of the 20th century due to an influx of migrant workers from the countryside. The city is ringed by dozens of slum neighbourhoods (*barrios marginales*) lacking connection to municipal water supplies. This means that state subsidies to the water utility went mainly to support industry and middle class neighbourhoods. The poor neighbourhoods managed to secure water supplies from communal wells that were drilled with the help of foreign aid and were maintained by local water cooperatives.

In 1997, conditions on the World Bank US $600 million loan for debt relief included the privatization of the water supply for Cochabamba, and two years later a private consortium *Aguas del Tunari* (majority owned by the US-based Bechtel Corporation) was granted a 40-year concession contract to rehabilitate and operate both the municipal water supply network and all the smaller ones. The contract provided for exclusive rights to all the water in the district including the aquifers used by the water cooperatives. Meters were installed on community wells and within a very short time water supply prices were raised by amounts that, while ”modest’ for high volume users, effectively denied access to safe drinking water for the poor. Workers living on the local minimum wage of US $60 per month were faced with water bills that consumed 25% of their income. In 2000, a broad coalition of workers, farmers and environmental groups formed the “*La Coordinadora*” that organized a general strike and massive protests in opposition of the rate hikes. A “water war” (Finnegan, 2002) erupted with battles on the streets and mass arrests.

Martial law was soon declared but this failed to stem the protests. *Aguas del Tunari* decided to abandon the city, and the government revoked the concession contract. *Aguas del Tunari*, essentially a team of engineers brought in from overseas, had given little thought to how its plans would be received in the city, and its operation, however best intentioned, had been destined to fail.

Following the exit of *Aguas del Tunari*, responsibility for Cochabamba’s water supply was returned to the old public utility SEMAPA which was thoroughly overhauled. The government also introduced a law that granted legal recognition to traditional communal practices and ensured protection of small independent water systems. Nine years later, SEMAPA continues to suffer from all of the problems that seem to plague public utilities throughout the developing world: unmanageable debt, water losses through leakage and infamously poor service. The new SEMAPA, having driven away investment, finds itself desperately in need of new capital. It seems the Cochabambinos may have won the battle against privatization in the streets (Kohl, 2004) but have lost the war in their efforts to secure a fair and affordable water supply.

3.9 Some of the lessons learned

A striking characteristic of many of the case studies presented here is the resilience and resourcefulness of water users in the face of water adversity. While many of the actions can be considered unlawful – in the sense that wells are often drilled without permits and appropriate fees are rarely paid, especially for illegal connections to mains supplies –, the pooling of significant financial resources to construct a well and set up pipe networks demonstrate a certain willingness to pay a fair price for water, at least amongst those who can afford it. The tragedy is that ”solutions” involving the use of groundwater (or in the case of Bangkok, by banning the use of groundwater), as novel and creative as they may be, are entirely in response to a problem, e.g. lack of access to water or serious environmental degradation. The real challenge is to create <u>proactive</u> solutions that are part of a pre-conceived water resource management plan – a plan that considers both quality and quantity aspects and is developed in close collaboration with all stakeholders using good data, sound science and reliable demographic projections. Moreover, this plan needs to be fully embedded in the urban planning process. This challenge - and opportunities to meet this challenge - is explored in Chapter 4. Much of the discussion on governance in Chapter 4 is based on the strategic overviews, briefing notes and case profiles published by the World Bank’s Groundwater Management Advisory Team GW-MATE (Foster *et al.*, 2010c).

4 Groundwater Governance and Opportunities for Rural-Urban Co-Management

4.1 Mechanisms for reducing tension

The core challenge for good governance of urban water supply includes an urgent need to identify and prioritize the courses of action required if continued growth of the world's cities is to be sustained. Urban-rural tensions are an inevitable consequence of growth and a frequent root cause of such tensions is "water scarcity" i.e. the lack of access to an adequate supply of suitable quality water. In such cases, problems are heightened in peri-urban areas where urban, industrial and agricultural users directly compete for the same resource. In other cases, water scarcity relates more to the inefficient water distribution system (reticulation networks – tanker supplies) than it is by the total size and quality of the water resource. It is this type of water scarcity that has driven the explosive increase of private in situ water wells in many cities throughout the world.

If the world's rapidly growing cities are to be provided with adequate supplies of potable water on a sustainable basis, then urgent solutions are required. These solutions are undeniably complex given that many cities face competing political, societal and economic interests and limited financial resources for technological innovation and essential infrastructure. However, the choices are relatively simple and can usually be categorized into three basic options (Sharp, 1997):

- increase the available water supply;
- temper water demand (demand management);
- manage the water resource more efficiently.

Increasing the available water supply
The availability of the water supply can be increased by various methods including but not limited to:

- new groundwater resources;
- resource mining;
- aquifer recharge management using artificial recharge;
- water blending;
- substituting poorer quality water for some uses.

Locating new groundwater resources may not represent a serious option for cities facing severe overdraft problems. However, for many cities, it is a potential solution that is too often ignored in favour of alternative, surface water sources. Imported surface water may provide reliable, short-term benefits but can be unreliable in the longer term. Intensive use of groundwater (groundwater mining) is always an important option as it can facilitate economic growth, while allowing postponement of investment in dams, long distance transfers, desalination plants, etc. However, it needs to be positively planned and realistically evaluated, and close control over groundwater production must be exercised. There must also be a clear and feasible plan for alternative water supplies when the groundwater resources are exhausted. There is not a prosperous nation in the world that has not benefited at some time from intensive use of groundwater, although mostly due to an ignorance of the hydrogeology and associated long-term risks than through a carefully evaluated and planned production strategy.

A more permanent solution is to augment the resource through artificial recharge or "managed aquifer recharge" (MAR) (Ward and Dillon, 2011). Urban areas are net 'creators' of water since the very limited vegetation and extensive impermeable surfaces return relatively little of the incoming precipitation to the atmosphere as evapotranspiration. Modern technologies allow the resulting storm water runoff to be directed into the subsurface for storage and ultimately use. Artificial recharge is not limited to storm water; treated wastewater can be 'polished' to potable standards using MAR techniques.

An important consideration is that the vast majority of water used globally does not need to meet potable water quality standards. Too much potable water quality is used for industrial, agricultural and many urban purposes when poor quality water would readily suffice. In effect, if alternative water sources of lower quality water could be directed to meet at least some of these needs, significantly more potable water would be available to meet human demand for safe water. An alternative means of making good use of inferior quality water is to blend it with good quality water in such proportions that the water meets water quality guidelines that are appropriate for its intended use. Ideally, this would require that a suitably located and carefully protected 'external well-field' be established as a stable source of high-quality supply.

Demand management

Demand for groundwater can be tempered through a wide variety of measures. Typically they include:

- limiting the number and depth of wells through controls on the issue of well construction permits;
- limiting accessibility to municipal supplies to certain periods of the day;
- price structuring (e.g. water metering and tariffs);
- water conservation (e.g. use of technologies that use less water to perform the same task).

In many developing countries, per capita usage of water is already very low, and there are few opportunities for significant savings to be made at the domestic level by adopting water conservation practices unless major incentives for reducing water use are established. Some reduction can be achieved by limiting household accessibility to water to just a few hours each morning and evening, as is practiced in India (Limaye, 1997). Unfortunately, this does little to control usage when water is actually made available.

At the communal and municipal level, demands on the aquifer can be reduced by limiting pumping. However, according to Morris *et al.* (1997), this is better achieved by strict controls on the construction of water wells (through licensing) as opposed to simply restricting pumping rates via permit for wells that are already constructed. Many argue that it is pointless to regulate water usage if laws are not adequately enforced and violators are not prosecuted. Limaye (1997) argues that the greater the number of rules and regulations, simply the greater the level of illegal activity.

Perhaps the most effective means of controlling demand is the disincentive that results from increased water tariffs. As described by Morris *et al.* (1997), this can be achieved at the wellhead by imposing realistic charges for raw water based on one or more of the following:

- recovering full costs incurred by the regulatory body for administering resource development and evaluating, monitoring and managing the groundwater resource;
- including the potential cost of providing alternative raw water supplies to users in the event the source goes out of commission;
- acknowledging the full cost of environmental impacts that will likely accrue due to the water undertaking.

Pricing water based on the quality and quantity of water pumped at the wellhead provides an incentive for more effective demand management including the reduction of leakage from pressurized water-mains. In many large cities leakage rates exceed 30% and can cause additional problems to city infrastructure such as flooded basements, tunnels and underground electrical utilities. Water pricing can do little to encourage water conservation at the consumer level, however, unless the charges can be passed on to these users equitably according to the actual amounts used. This requires individual metering, which can be expensive to install and maintain, but is a proven means of reducing wastage. Unfortunately, domestic metering is such an administrative burden that many fees go unrecovered. The exercise may also prove counter-productive if user fees exceed what the user can realistically afford to pay. In all cases, education is a crucial starting point as an informed public can be an accepting public. Education in good, responsible water management practices and the need for such practices must be focused at all levels of government, industry and the population at large.

Efficient management of the resource

Ultimately there are limits to which supply can be increased and demand reduced. The long-term sustainability of groundwater supplies for growing cities requires that groundwater be managed far more efficiently. This means that water quality impacts must be minimized and that available water reserves must be managed to maximize their utility. Recognizing that surface water is an important component of the urban water cycle and a critical water source for most cities, significant additional management benefits can be obtained by optimizing their combined development through conjunctive use (Paling, 1984). Conjunctive use recognizes the interdependency between the ground and surface water resources of a basin and ensures that maximum benefit is obtained by integrating ground and surface water resources into a single resource management plan. To date, unfortunately, most conjunctive use encountered in the developing world amounts to a "piecemeal coping strategy" (Foster *et al.*, 2010b) in response to an urgent resource problem.

According to Barber (1997), management of our groundwater systems should be underpinned by science. The role of the scientist is to address perceived problems and develop solutions that can be used by resource managers. Management practice can then evolve by incorporating scientific developments into an overall strategy to achieve best-available practice. Fortunately, the science is well advanced and there is a wealth of excellent ground and surface water modelling tools that can be used for:

- quantifying the water budget;
- performing vulnerability assessments and identifying "ZOCs – zones of contribution" - areas around wells most in need of protection;
- predicting groundwater travel times for contaminants in the system;
- determining "optimal" pumping and water extraction rates; and
- testing and evaluating alternative water management scenarios.

Despite a critical lack of reliable data for urban areas, these models can greatly assist in the development of management programmes and provide support for decision-making. 'Assist' is the key word since the formulation of appropriate management action plans is as much social as it is technical. It is a long-term process that demands sustained national and international political commitment, social consensus and substantial improvements in the types of data so essential for resolving complex aquifer flow dynamics and the patterns of socio-economic demand that are placed upon the resource. Waiting for data, however, is not an excuse to delay action (Burke and Moench, 2000).

There is a strong school of thought that strategies for groundwater management are most effective when they:
- are developed in close co-operation with stakeholders, and
- fully acknowledge economic, social and political conditions.

This philosophy equally applies to aquifer [water quality] protection plans that should form an integral component of groundwater management. Traditionally, water projects in developing countries have been instituted using the "top down" management approach that rarely considers the interests and specific needs of the individual users, but satisfies, at least in principle, the goals and aspirations of government officials, consultants and support agencies. In the poorest countries, the interests of stakeholders, including users within the local communities, are totally ignored. According to the principle of participatory management, first introduced at the 1992 Dublin International Conference on Water and the Environment, the development of water policy should adopt a participatory approach that involves users, planners, and policy makers at all levels. Most importantly, the participatory approach would require that decisions be taken at the lowest appropriate level which, in practice, means the direct involvement of local and regional agencies representing community interests. All stakeholders must be satisfied that their needs are being met as ultimately, workable solutions will not be forthcoming without the full commitment and co-operation of all levels of government, industry and the population at large. In effect, current problems with urban groundwater management will not be resolved until governments seek to work with groundwater users and resist trying to regulate and control them.

4.2 Groundwater governance

Groundwater is a classical 'common pool resource', a term used to describe a natural resource whose size or characteristics makes it virtually impossible to exclude potential beneficiaries from deriving benefits from its use. Such resources are vulnerable to the so-called 'tragedy of the commons' (Harding, 1968) in which actual and potential stakeholders act solely in their own individual short-term self-interest rather than taking into account long-term communal requirements. While Hardin recommended that the tragedy of the commons could be prevented by either more government regulation or privatizing the commons property, Ostrom (1990; 2005) suggests that simply passing control of local areas to national and international regulators can generate even greater problems. Ostrom argues that the tragedy of the commons may not be as prevalent or as difficult to solve as Hardin implies, since locals often demonstrate an ability to find solutions to the commons problem themselves; when the commons is taken over by national regulators, those solutions can no longer be used. Ostrom's work provided a series of design principles for stable local common pool resource management (Ostrom, 1990, 2005, 2009a and 2009b). In terms of groundwater governance, the "Ostrom Principles", provide a practical guide to cooperative groundwater management and are especially appropriate for urban groundwater management given the multitude of potentially competing interests. Based on the Ostrom principles the management approach would involve (Foster *et al.*, 2010a):

- clearly-defined boundaries for resource evaluation and allocation, and congruence with prevailing local conditions and constraints;
- formal recognition by government of the water management rights of the community;
- collective arrangements for decision making;
- layers of nested stakeholder groups to cope with larger resource systems;
- effective monitoring with stakeholder involvement;
- graduated sanctions on users who do not comply with communal rules; and
- low-cost, efficient conflict-resolution mechanisms.

The character of groundwater also means that links with the governance of the environment, and other land and water resources, are decidedly relevant. For example, groundwater resources are highly dependent upon land use in the main 'aquifer recharge areas' and any changes in land-use can significantly affect both the rates and quality of recharge. Thus, groundwater governance cannot be addressed without due consideration for the processes that determine or control land use. In urban areas, land use is generally controlled by the municipal or local government, and the absence of mechanisms whereby water resource agencies can influence land use planning is a common governance weakness. By the same token, the groundwater supply for many urban areas is obtained from peri-urban well-fields such that rural land-use practices and the intensification of agricultural production (largely determined by national agriculture and food policy) exert a very strong influence on groundwater recharge rates and quality.

It is also important to appreciate the effect 'cross-sector drivers' may have on groundwater resource use and pollution potential since it is likely that provisions will be required to influence associated macro-level policy decisions.

Figure 7 shows the key elements required for the development and implementation of an "Action Plan" for sustainable groundwater management (Foster *et al.*, 2010a). While there can be no 'one-size-fits all' when it comes to models of groundwater governance, Figure 7 provides a blueprint for developing governance structures for a range of situations including urban areas. Significantly, the starting point must always involve a thorough understanding of the resource setting. It will include the definition of the manageable groundwater bodies[4] , and will be followed by assessments of the hydrogeologic condition and socioeconomic situation. These factors, in essence, define the problem and shape the solution.

The cumulative operational experience of GW-MATE in assessing the effectiveness of existing provisions and capacity for the exercise of adequate groundwater governance (in areas where groundwater resources are experiencing significant stress from intensive development and/or pollution pressure) has been distilled into a priority list of benchmarking criteria. These are shown in Table 6 (Foster *et al.*, 2010a).

Primary considerations include:

1) Institutional and Legal Provisions
   Foster *et al.* (2010a) suggest that in assessing the current status of governance provisions, careful distinction should be made between:
   - the institutional framework: the national and/or state constitution and related government structure;
   - local organizational arrangements, i.e. organization for water resources management and water services provision at a lower level;
   - primary legislation: the legislative material (such as the Water Law) as approved by the legislature, which states policies, principles, approaches and mechanisms; and
   - legal regulations: legislative materials issued by the executive to explain implementation details, as empowered by the primary legislation.

[4] *'Groundwater bodies' are defined as resource management units with clearly-defined and scientifically-sound boundaries (usually parts of aquifer systems), which can be related, as necessary, to the overall basin in which they occur.*

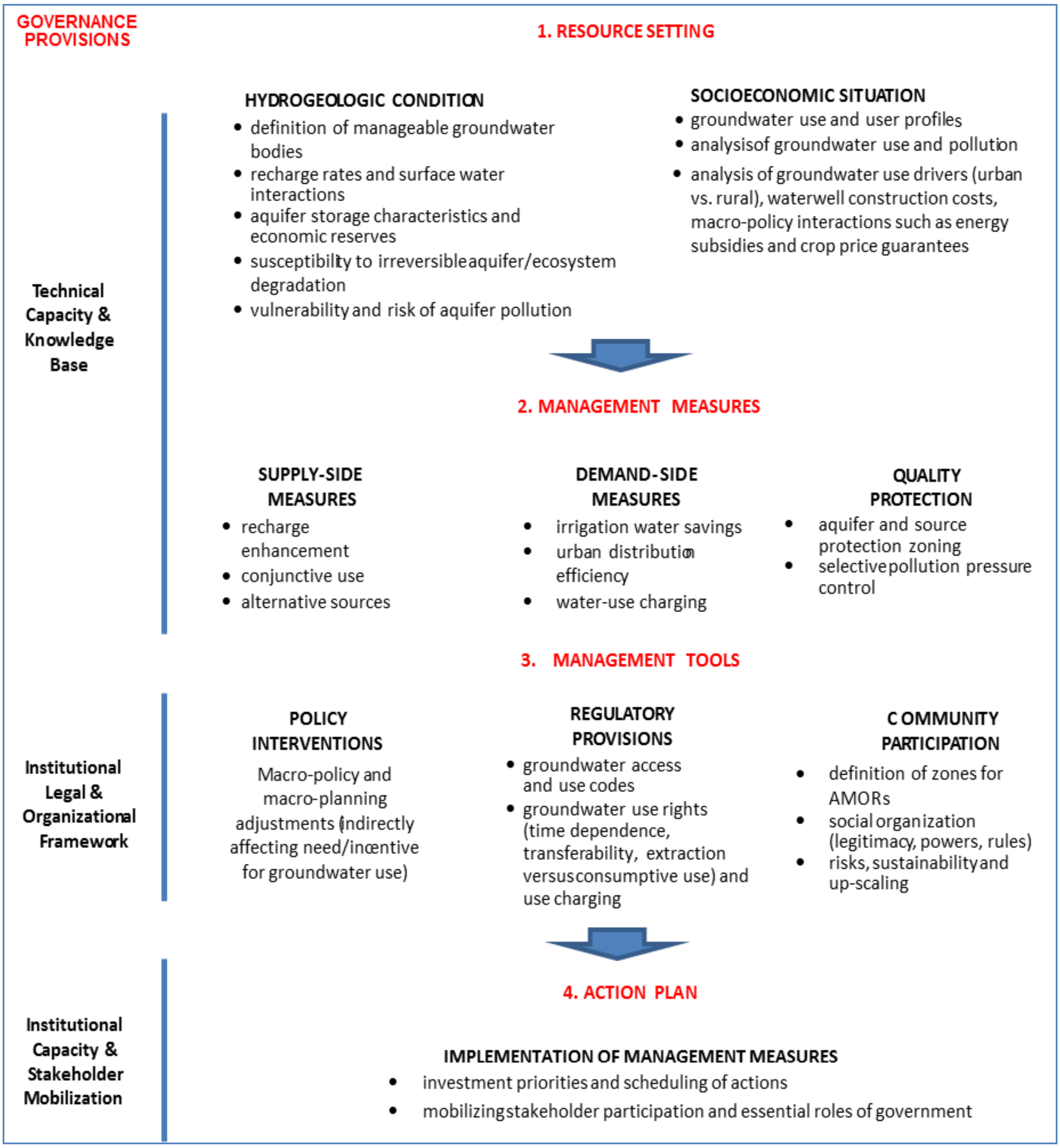

Figure 7. A framework for the development and implementation of a groundwater management action plan with corresponding governance provisions (modified after Foster et al., 2010a).

They warn, however, that attempts to modify legal provisions and organizational arrangements for groundwater governance can be politically difficult and time consuming and they suggest a duel approach to the problem that seeks to make progress within the existing framework, while working in parallel on necessary legal reforms.

2) Provision for Stakeholder Participation

Since an important goal of groundwater management is to influence the behaviour of individual groundwater users and potential polluters, participation by representative stakeholders is a critical groundwater governance instrument. This is because:

- top-down management decisions taken unilaterally by regulatory agencies without social consensus are often impossible to implement; stakeholders need to feel a sense of ownership in key decisions.

- important groundwater management activities such as monitoring, policing and tariff collection can be carried out more efficiently and economically through cooperation;
- stakeholder participation facilitates the integration and coordination of decisions relating to groundwater resources, land use and waste management.

With respect to urban groundwater governance, it is essential that all users be adequately represented including peri-urban and rural users. Foster at al. (2010a) suggest that Water Users Associations (WUAs) responsible for the management of irrigation systems are not enough alone to ensure stakeholder participation for rural groundwater resources, and there is need of a system for higher-level user and stakeholder participation which they refer to as an "aquifer management organization" (AMOR) (see Figure 7). This would be formed at the initiative of the water resource regulatory agency, in which all WUAs and other main groups of stakeholder are represented. Based on their GW-MATE operational experience, Foster at al. (2010a) believe that while decentralised groundwater management with some form of stakeholder participation is the most appropriate management approach, national governments need to ensure state/provincial/municipal level agencies receive adequate funds to hire and retain the well trained professionals required to perform the necessary work.

Table 6. Check list of 21 key benchmarking criteria for the evaluation of groundwater governance provision and capacity (modified after Foster et al., 2010a)

TYPE OF PROVISION/ CAPACITY	CHECK LIST		
	No.	CRITERION	CONTEXT
	1	Existence of Basic Hydrogeological Maps	
	2	Groundwater System Conceptual Model Development	For identification of groundwater resources with classification of typology
	3	Groundwater Body/Aquifer Delineation	
Technical	4	Groundwater Potentiometric Head Monitoring Network	To establish resource status
	5	Groundwater Pollution Hazard Assessment	For identifying quality degradation risks
	6	Availability of Aquifer Numerical 'Management Models'	At least preliminary for strategic critical aquifers
	7	Groundwater Quality Monitoring Network	To detect groundwater pollution
	8	Water-well Drilling Permits & Groundwater Use Rights	For large users, with need of small users noted
	9	Instrument to Reduce Groundwater Abstraction	Water-well closure or constraint in critical areas e.g. overexploited or polluted areas
	10	Instrument to Prevent Water-well Operation	
	11	Sanction for illegal Water-well Operation	Penalizing excessive pumping above permit
Legal & Institutional	12	Groundwater Abstraction and Use Charging	"Resource tariff" on larger users
	13	Land-Use Control on Potentially-Polluting Activities	Prohibition or restriction since a potential groundwater hazard
	14	Levies on Generation/Discharge of Potential Pollutants	Providing incentive for pollution prevention
	15	Government Agency as 'Groundwater Resource Guardian'	Empowered to act on cross-sectoral basis
	16	Community Aquifer Management Organizations	Mobilizing and formalizing community participation
	17	Coordination with Agricultural Development	Ensuring 'real water saving' and pollution control
Cross-Sector Policy Coordination	18	Groundwater-Based Urban/Industrial Planning	To conserve and protect groundwater resources
	19	Compensation for Groundwater Protection	Related to constraints on land-use activities
Operational	20	Public Participation in Groundwater Management	Effective in control of exploitation and pollution with measures and instruments agreed
	21	Existence of Groundwater Management Action Plan (see Figure 7.)	

4.3 Urban groundwater governance issues – within city limits

Few groundwater-dependent cities are able to obtain adequate supplies from within city limits, but those that do need to maximize the quantity of the available resource while safeguarding water quality. Unfortunately, there is all too often a vacuum of responsibility and, therefore a lack of accountability, for urban groundwater. For example, groundwater use sustainability can be greatly influenced by a wide array of local developmental decisions, which are rarely examined in an integrated way, including:

- production and distribution of water-supplies (by municipal water-service utilities and public-health departments);
- urbanization and land-use planning (by municipal government offices);
- installation of sewered sanitation, disposition of liquid effluents and solid wastes (by environmental authorities, public-health departments and municipal water-service utilities).

It means that, at best, responsibility for the sustainability of groundwater supply is divided between a number of organizations, none of which is normally willing or indeed capable of taking the lead necessary for coordinated management action. Typically, these organizations include municipal water-service utilities, provincial/state government water-supply and public-health engineering departments, central and/or provincial/state/basin groundwater resource agencies and environment protection/pollution control agencies. Municipal water-service utilities are usually best equipped to handle the engineering of water-well construction and operation, but rarely show interest in understanding and managing the resource base. It means that the criteria for water-well siting and construction are normally based on efficiencies of cost and are not considered in terms of optimal use of the groundwater resource. It is said that "urban groundwater tends to affect everybody, but is often the responsibility of 'nobody'." This clearly needs to change.

Foster *et al.* (2010b) recommend the following policy actions to ensure physical sustainability of the urban groundwater resource base:

- defining areas with critical levels of resource exploitation as a basis for restricting further development;
- providing clear criteria by area for issuing of water-well permits (in terms of safe separation and maximum pumping rates);
- controlling municipal and private groundwater abstraction on the basis of defined areas – including the relocation of municipal water-wells, increased resource-use fees, and (even) closure of private water-wells where local conditions so merit;
- maximizing use of aquifer recharge enhancement techniques taking provisions to avoid groundwater pollution;
- monitoring and periodic evaluation of groundwater resource status, including the use of numerical aquifer simulation models.

In addition, they suggest a much more integrated approach to urban water-supply, mains sewerage provision and land use is required to avoid persistent and costly problems. This would include the following types of measure:

- prioritizing some recently urbanized areas for coverage by mains sewerage so as to protect their good quality groundwater from gradual degradation;
- establishing municipal source protection and/or exclusion zones, especially around any municipal water-wells that are favourably located to take advantage of parkland or low-density housing areas;
- assessment of the sanitary protection standards of municipal water-wells and the risks of wellhead contamination, and how they can be reduced;
- undertaking groundwater pollution vulnerability mapping and hazard assessment, and being prepared to abandon some municipal water-wells where the contamination risk by toxic synthetic substances is very high;
- avoiding creation of polluting discharges in 'upstream areas' that could percolate and compromise the groundwater quality of municipal water-wells.

A common problem in the developing world is that the vast majority of private urban water-wells are either illegal or unregulated, a situation that is counterproductive for both the private user and the public administration. Where appropriate, a more constructive approach would be to legalize such wells. This would allow:

- urban groundwater users to receive sound information and advice relevant to their use (pollution risks/alerts, use precautions, etc.) and be protected against the impacts of excessive total abstraction and/or inadequate well spacing;
- sanitary completion standards for water-wells to be improved and their potential interaction with in-situ sanitation units (latrine, cesspools, septic tanks, etc.) reduced;
- the public administration to obtain better data on private use and establish better relationships with private users and well drillers and pump suppliers;
- opportunity to collect information on water quality.

In terms of aquifer management, water-supply security can be significantly enhanced by:

1) Adopting an adaptive water resource management approach (Gleeson *et al.*, 2012) that allows decision-makers to adjust and fine-tune the management plan (the Adaptive Management Plan – AMP) approach as more is learned about the aquifer and its behaviour. The AMP however should never be considered as a convenient substitute for a full scientific understanding of the aquifer system but instead as an opportunity to refine a fundamentally robust management plan as more data on groundwater levels and aquifer trends become available.
2) A carefully conceived program, well supported by long-term data that optimizes ground and surface water resources through conjunctive use.

The best aquifer management plans are underpinned by a transient numerical aquifer model – a "decision-support tool", calibrated with historic groundwater abstraction and drawdown data. This model would be used to explore management options with the AMP, including prospects for conjunctive use. It would also be used to examine the opportunities and risks associated with intensive groundwater use.

In summary, groundwater is a fundamental component of the urban water cycle and the overall challenge is to fully integrate groundwater into urban land-use planning, water supply and waste management, whatever its status (Table 7). Groundwater is far more significant in the water supply of developing cities and towns than is appreciated. However, organizations responsible for urban water-supply and environmental management often have a poor understanding of groundwater and its unique attributes. This lack of understanding often leads to groundwater pollution most notably related to inadequate *in situ* sanitation. Because contamination of large aquifers occurs slowly, and out of public sight, it may be decades before the problem is fully manifest. By such time, full remediation of the problem is likely to be prohibitively expensive. Whichever model of governance is selected for urban groundwater management, there can be no substitute for knowledge and understanding of the aquifer system and a sound groundwater database.

4.4 Urban groundwater governance issues beyond the city limits – opportunities for rural-urban co-management

Most groundwater-dependent cities are ultimately reliant on external aquifers over which they may have little, if any, jurisdiction or influence. Recognizing the huge demand for groundwater in rural areas to meet agricultural needs, an unhealthy competition for the resource is emerging in many towns and cities, with those living at the RUI and in peri-urban areas at the heart of the conflict. Not surprisingly, there are two diametrically opposed perspectives to this urban-rural issue.

Rural communities believe that the economic and power dynamics of this competition leaves them at a disadvantage because they cannot generate comparable financial returns or are less represented in positions of power (lobby groups, politics, etc.) and unable to influence water allocation. Studies have shown, for example, that water exported from rural areas to urban centres leads to food insecurity and unemployment (IFAD, 2001). Farmers well recognize that contamination of groundwater represents the greatest threat to their livelihoods and that groundwater used in rural areas on the periphery of cities is seriously threatened by polluted urban runoff or leaching of contaminated water from urban pollutant sources (Nagaraj, 2005). They find that regulation of groundwater is very difficult due to the number of actors involved. NGOs, foreign government assistance programs and private companies often act independently and work with different

Table 7. Summary of major policy issues associated with urban groundwater (after Foster et al., 2010b)

MAJOR POLICY ISSUES ASSOCIATED WITH URBAN GROUNDWATER	
ISSUE	**IMPLICATIONS**
Municipal Water-Supply Benefits	Groundwater use for municipal water-supply has many benefits (including capacity to phase investments with demand growth and high quality requiring minimal treatment) but it usually comes with a need for integrated planning of urban land-use, effluent discharges and solid-waste disposal to avoid insidious and near irreversible degradation by pollution.
Private *In Situ* Use Benefits & Hazards	Private *in situ* use for urban residential, commercial and industrial water-supply can have significant benefits not only to the user but to the community (reducing demand on utility supplies, providing water in areas or volumes difficult for the mains network, not using high-quality mains water for garden irrigation and commercial / industrial cooling) and these benefits need to be valued in terms of the marginal cost of providing a volumetrically-equivalent alternative water-supply – but poorly-constructed and shallow urban water-wells can present a significant health hazard due to faecal contamination (in serious waterborne disease outbreaks) or chemical contamination (especially in areas without mains sewerage).
Water-Sector Financial Considerations	Widespread self-supply can have major financial implications for water-service utilities, in terms of loss of revenue from potential water sales, difficulties of increasing average tariffs and recovering sewer-use charges from those operating private water-wells.
Conjunctive Use with Surface Water	The rates of replenishment of aquifers may not be sufficient to meet the demands of larger cities sustainably and in this situation it is preferable to use available groundwater resources and large storage reserves conjunctively with surface water sources – conserving groundwater for use during drought and other emergencies.
Future Drainage Problems	Should abstraction radically diminish (due to an increased offer of subsidized mains water-supply or to quality deterioration or pollution rumours) then groundwater levels will rise progressively to higher than the pre-urbanization condition, potentially with serious sanitary problems and infrastructure damage in lower-lying areas.
Protected Municipal Well-Fields	Since some degradation of groundwater quality in urban municipal water-wells due to persistent pollutants is likely, it is necessary in parallel to develop 'external well-fields' and declare their capture areas as 'protected zones' to guarantee that a proportion of the total resource is of high quality and available for dilution or substitution.

government ministries when implementing their agendas. The lack of coordination prevents responsible resource management and promotes depletion of aquifers. Individual rural users who typically use their shallow wells for domestic supply and small-scale livelihoods are the first to be affected by lowered water tables.

From an urban water supply perspective, cities believe that activities in peri-urban and rural areas pose a serious threat to the sustainability of their supply. For example, over-pumping often invites groundwater salinization, and agriculture can lead to contamination by fertilizers, pesticides, herbicides and, in some cases, wastewater. They recognize, as a best management practice, the need to protect peri-urban well fields through regulation, e.g. with their capture areas declared as ecological or drinking-water protection zones. They find, however, that any attempt to establish procedures and incentives for resource protection often encounters administrative impediments related to fragmented powers of land use and pollution control. Too often, there is an enormous disconnect between water and land use regulations.

The solution to this apparent impasse is co-management of the groundwater resource at the catchment scale with strong representation of all stakeholders. In some respects, the approach would be similar to that involved in managing transboundary aquifers, except that the border is the rural-urban interface and the players involved are somewhat different. As indicated previously, there is no one-size-fits-all solution when it comes to groundwater governance. However, a recent study of rural-urban co-management opportunities that was recently conducted in the city of Zhengzhou, China (Sun *et al.*, 2009a) demonstrates some of the key institutional and policy considerations. As described briefly below, it shows how a balance can be achieved between urban and rural use as a means to sustainable development based on integrated groundwater-surface water and urban-rural management principles.

Zhengzhou (pop. 7.2 million) is located in the lower reaches of the Yellow River in water-scarce northern China. It has a total area of 7 446 km^2, about 15% of which is occupied by the city of Zhengzhou, the capital of Henan province. 39% of Zhengzhou's population live within city limits and 61% reside in the surrounding rural area.

Groundwater represents about 70% of Zhengzhou's water supply. Just over 50% of the groundwater is used for agriculture (down from 58% in 1995) while industrial and domestic uses are 3% and 17% respectively. Despite many attempts to conserve water by controlling development, groundwater remains over-exploited and many environmental problems related to over-development exist. Between 1990 and 2000, the number of tube wells increased from 37,164 to 42,763 resulting in a lowering of the water table and a shift from shallow to deep tube wells. Most of the new deep tube wells were funded by the government or village collectives (Sun *et al.*, 2009b). Shallow-groundwater quality is also a problem. In the city, pollution sources include wastewater from industry and domestic sewage, while in rural areas the problem is agricultural fertilizer, pesticides, and wastewater from livestock. According to the Water Resources Bureau of Zhengzhou, 1,5 million farmers (38% of all farmers) do not have access to safe drinking water from ground or surface sources.

In theory, at least, many of the problems could be resolved by requiring that all water-resources management including groundwater should be under the Ministry of Water Resources and its provincial and local arms. The reality, however, is that like in most of the world (Nanni and Foster 2005) management is scattered amongst a multitude of agencies, many with overlapping responsibilities. Insufficient communication and, in some cases, competing interests have resulted in groundwater regulations and policies being ineffectively implemented or even conflicting. For example, one agency in Zhengzhou was working to close urban tube wells while others continued to open new wells. Unfortunately, the development of an "ideal" model of truly integrated groundwater management is unrealistic in practical terms, both for the short and long terms. However, a reasonable goal is the building of institutional frameworks under which ministries and agencies with differing mandates and goals can share information on the state of groundwater resources and the impacts of use, thereby generating at least partial coordination of policies for groundwater management. Sun *et al.* (2009a) suggest that within Zhengzhou, the Water Resources Bureau of Zhengzhou could take the lead and serve as a focal point for communication and coordination of the ground-water functions and policies of the other various actors involved in the areas of groundwater management.

It is the coordination of functions and polices that provides the key of opportunity for co-management of rural and urban groundwater use within those agencies, as well as the opportunities for urban-rural conjunctive use. For example, wastewater treatment and the reuse of domestic and industrial wastewaters for irrigation in rural areas can improve environmental conditions while reducing the demand on groundwater. Provided it is not seriously degraded, surface water is generally more appropriate for irrigation purposes, with good quality groundwater best reserved to meet more demanding domestic and industrial needs (Villholth, 2006). However, in practice, the reverse tends to occur because farmers find it convenient to draw groundwater from a well close to their fields, while water intakes for central municipal water-supply distribution systems may well be taken from larger rivers. Co-management of the resource would provide a net benefit ensuring more surface water and treated wastewater is used for agriculture while groundwater urban users have priority over groundwater.

Sun *et al.* (2009a) suggest that co-management of urban and rural groundwater may also reduce the overall costs of groundwater management, indicating that most management efforts tend to focus on urban areas with their relatively higher economic output. They suggest that a proportionately higher gain may be obtained from investing in water saving technologies and cropping reforms in rural areas that could lead to real water savings that in turn could benefit urban water supply. Incentives would be required to encourage adoption of water-saving technologies and this is often best achieved through pricing and cost controls. Another option for increasing water-use efficiency while protecting farm income is to give farmers an opportunity to benefit from increases in water prices by allowing them to sell 'their' water. However, this would need to be carefully regulated to avoid excessive exploitation.

It is concluded that co-management of urban and rural groundwater is a worthy goal with many potential benefits for all users. However, this would need significant reform of the institutional arrangements that exist for most developing cities, together with a closer re-alignment of management objectives. Important first steps should include increased public awareness, concerted dialogue amongst stakeholders and data sharing amongst agencies that have an interest in water management. The starting point for co-management is cooperation.

5 Conclusions

Global population growth has placed a huge burden on supplies of fresh, available water. In many countries, increasing competition for water between agriculture, industry and domestic needs threatens economic development, food security, livelihoods, poverty reduction and the integrity of ecosystems. Within 20 years, the global population is projected to rise from 7 billion to 8 billion with all this growth taking place in urban areas.

The scale of urbanization poses monumental opportunities and challenges (SIWI, 2011). Most of the world's urban growth occurs in developing countries, where well-serviced centres are surrounded by expanding stretches of under-serviced suburbs and peri-urban slums. Since there is no international agreement on how to define 'urban' limits, many suburban and peri-urban areas are seriously neglected when it comes to urban planning and the provision of adequate water services. Successful, developed-world strategies for urban development simply cannot be replicated in less developed countries where a serious disconnect between water management and urban planners is well documented. In many cases, there is no urban planning at all. Without the planning of urban space and infrastructure, opportunities to provide adequate water and sanitation services are seriously compromised.

History has shown that where urban water delivery services are positively planned, centralized systems of water service approach often fails. In response, many countries adopted a "decentralized" approach but these have shown mixed success with affluent residents often enjoying significantly better access to water services than the poor or those from rural areas. In many cases, decentralization has failed because financial resources have tended to remain at the central level and the transfer of important decision-making responsibilities to district and village levels has not been followed by the transfer of funds for essential capacity development.

A compounding problem in the global effort to supply rapidly growing cities with water and sanitation services has been the failure to consider the fundamental nature of the resource and show respect for the fundamental differences that exist between surface water and groundwater as sources of supply. Concern for urban population growth and the need to address increasing demand for water have been high on the global water sector agenda for more than twenty years. The "global urban water crisis" has been well documented and the lack of good water governance has been cited as an underlying problem in urgent need of attention. However, virtually all the debates on global water policy that have raged at international water meetings during the past two decades have remained transfixed on surface water issues. The role and importance of groundwater has been practically ignored. Integrated Water Resources Management (IWRM) and its multi-faceted, integrative approach to water systems management has been widely publicised as the solution to the world's water issues, but in truth it has not served us well in the urban areas of the world. This is because IWRM gives very little recognition to the vital function that groundwater plays in the global water cycle and the immense benefits that could be derived from the improved management of groundwater. A failure to recognize the unique and special attributes of groundwater represents one of the lost opportunities of IWRM.

To some extent, the neglect of groundwater reflects an "out of sight, out of mind" mentality, which has promoted ignorance for water movement in the subsurface. However, neglect has also arisen because groundwater and surface water systems are spatially distinct and, in terms of water flow velocities, operate on totally different time scales. Reasons aside, the unfortunate consequence is that tools for urban water management rarely, if ever, incorporate an adequate understanding of aquifers either during the analysis stage or, just as importantly, during the subsequent management decision-making. For example, groundwater resources are highly dependent upon land-use in the main 'aquifer recharge areas' such that any change in land use can significantly affect both the rates and quality of recharge. This means that groundwater governance cannot be adequately addressed without considering the processes that determine land-use. In urban areas land-use classification and control are generally the domain of municipal or local government, and the absence of mechanisms whereby water resource agencies can influence the process is a frequent governance weakness. Similarly, groundwater supply for many urban areas is obtained from peri-urban well fields such that rural land-use practices and the intensification of agricultural production (largely controlled by national agriculture and food policy) exert a very strong influence on groundwater recharge rates and quality.

Fortunately, some excellent work has been conducted on groundwater governance during the past ten years, notably by the World Bank's Groundwater Management Advisory Team (GW-MATE) and others. This work has raised the profile of groundwater in the political arena and drawn attention to the widespread use of groundwater in many of the world's most impoverished cities, and has provided excellent blueprints for building appropriate governance structures and the various roles that must be played. These blueprints are founded on a realization that current problems with urban groundwater management will be resolved only if governments work with groundwater users rather than attempting to regulate and control them. In all cases, an effective groundwater management action plan is required that needs to be developed with or in close consultation with stakeholders. This must include the representation of both peri-urban and rural users. Top-down management decisions taken unilaterally by regulatory agencies without social consensus are often impossible to implement. Stakeholders need to feel a sense of ownership in the plan and the decisions that are made.

Good urban groundwater governance and the development of appropriate groundwater management action plans must begin with a fundamental understanding of the resource setting. The resource setting will include both the hydrogeological conditions (aquifers, recharge rates, economic reserves and vulnerability to pollution) and the socio-economic situation (demand, users and groundwater-use drivers, such as well construction costs and energy subsidies). In turn, a sound knowledge of the resource setting will lead to the identification of various management measures related to: a) the supply side (e.g. recharge augmentation and conjunctive use); b) the demand side (e.g. water use tariffs); and c) sustainable water quality (e.g. well head protection). It is essential that the technical capacity to deliver the necessary knowledge base be in place. National governments need to ensure state/provincial/municipal level agencies receive adequate funds to hire and retain the well-trained professionals required to perform the necessary work. Whichever model of governance is adopted for urban groundwater management, there can be no substitute for a sound knowledge and understanding of the aquifer system.

Ultimately, good governance and the successful implementation of urban groundwater management plans require the establishment of appropriate institutional frameworks. These would normally include departments and agencies at the national and/or state level working interactively with regional and city governments. The latter would normally be obliged to help execute national state policies while assuming various degrees of responsibility for the provision of water services and the development/implementation of water management plans. Many institutional models can be found and clearly, there is no "one-size-fits-all" solution. Based on their GW-MATE operational experience, Foster *et al.* (2010a) support a decentralized approach to groundwater management that includes effective stakeholder participation. They go on to warn, however, that attempts to modify legal provisions and organizational arrangements for groundwater governance can be politically difficult and time consuming, and instead propose an approach to the problem that seeks to make progress within the existing framework, while working in parallel on appropriate legal reforms.

Since many of the world's groundwater-dependent cities rely to a large extent on peri-urban well fields, there is a particularly urgent need to work with peri-urban and rural communities to ensure that resources are adequately protected and that the needs of both sets of users are adequately met. While this can be achieved to some extent by broad stakeholder participation, the ultimate challenge will be to develop aquifer management plans that provide for rural-urban co-management. While co-management of urban and rural groundwater is a worthy goal which may potentially benefit all users, this would need very significant reforms of institutional arrangements. Important first steps should include increased public awareness, concerted dialogue amongst stakeholders and data-sharing amongst agencies that have an interest in water management. The starting point for co-management is co-operation.

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Management of Aquifer Recharge and Discharge Processes and Aquifer Storage Equilibrium

Digest

Relevance of managing aquifer recharge, discharge and storage equilibrium for groundwater governance

Sustaining storage within aquifers is important for supporting groundwater dependent ecosystems and surface water resources, food production, drinking water supplies and groundwater-dependent economies. The absence of effective controls has led to widespread serious declines in aquifer storage. In almost all groundwater basins, groundwater depletion will become inevitable due to strong economic drivers for use, population growth, improved efficiency of groundwater extraction, and in some areas, a drying climate. Effective governance arrangements are vital for equitable groundwater sharing among the current population and with future generations. This will require a quantitative understanding of groundwater systems, informed communities and effective regulation of groundwater use.

However, Thematic Paper 4 gives ample evidence in many locations of good governance being effective in restoring depleted aquifers. Three tools for effective groundwater governance were identified: management of discharge, management of recharge and substituting alternative water sources (conjunctive use). These tools were used alone or in combination to effectively manage groundwater storage.

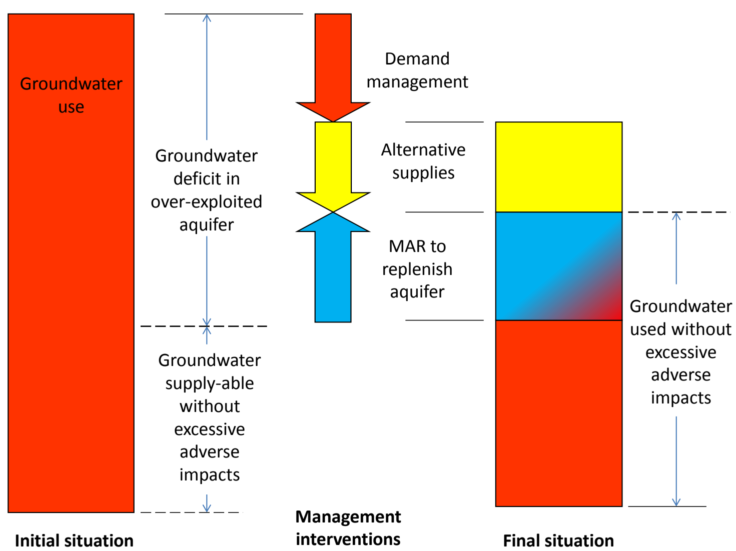

Figure 1. An aquifer can be brought into hydrologic equilibrium by either reducing extraction, or augmenting supplies, either through groundwater replenishment or providing alternative supplies.

Community engagement was important in all cases, and in some cases, local reforms were successful without reliance on state or national supporting policies. However national policies and frameworks would help make good governance ubiquitous.

Coverage: main aspects and dimensions

This scope of Thematic Paper 4 paper is global, covering case studies in countries in different continents, climatic zones and stages of development, and in rural and urban areas. It looks at the importance of each of the three tools used alone and in combination. While stressing the primacy of demand management, it gives particular emphasis to managing aquifer recharge, because this is an under-used tool among water resources managers even though it can be more economic than the more strenuous demand management measures. It can also be used as a lever to assist demand management, for example by pricing water to cover sufficient replenishment that gives groundwater users a beneficial return for their costs while also encouraging efficient use.

Surface waters, such as streams and lakes, urban stormwater, treated sewage effluent and desalinated seawater, can be recharged directly to aquifers or be a substitute for groundwater supplies (*i.e.* conjunctive use).Hence in temperate, semi-arid and even arid areas, where there is intermittent availability of any suitable source of surface water, managing recharge can be an effective part of groundwater governance. In arid areas with no alternative supplies, mining of groundwater needs careful management of water use to prolong the resource, increase its value, and plan for orderly closure of the resource.

Table 1. List of case studies, management instruments employed and their effectiveness

Case study	Demand management	Managed aquifer recharge	Alternative supplies	Effective-ness#
Ilocos Norte, Philippines	farmer led			yes
Andhra Pradesh, India	farmer led	localised		yes
Maharashtra, India	ban on tube wells and sugar cane	strategic		yes
Castilla y Leon, Spain	user collective failed to curb use	basins	treated wastewater	no
Namoi Valley, Australia	Entitlements issued		river water (also licensed)	yes
Kitui, Kenya		sand dams		yes
Coastal Bangladesh		recharge wells		yet to be assessed
Mancha Occidental, Spain		recharge wells	Guadiana channel	yet to be assessed
Bangkok, Thailand	Pricing to curb demand		treated surface water	yes
Alice Springs, Australia	Entitlements and use efficiency measures	minor soil aquifer treatment		yes for adopted objective
Arizona, USA	Groundwater rights assigned	water banking	CAP and treated wastewater	yes

 # storage objectives (and water quality objectives where known) are met and management process is accepted by groundwater users

Blank cells indicate that the particular governance instrument was not applied in that situation

Insight into constraints/ issues and limitations

Given that even chronic long-term groundwater depletion is a problem that has proven to be overcome by effective local groundwater governance, why are these demonstrated effective methods not in widespread use?

a) Prevailing unambiguous evidence is that having groundwater entitlements based on land-ownership, enshrined in law, fails to recognise the public good nature of groundwater and its essential role in sustaining streams, lakes, wetlands and ecosystems and fails to sustain storage. *The concept of a groundwater system being divided into fenced parcels with independent ownership is as absurd as the notion that a landholder would own migratory birds that rested on their property.* Information and legislative reform is necessary to empower effective water resources management.
b) A quantitative understanding of groundwater systems is necessary to define the allocatable pool. Very often there is little monitoring and recording of groundwater levels, and groundwater use is poorly quantified. These measures are necessary to provide assurance that groundwater users are equitably reducing their demand.
c) In some communities, groundwater users see themselves as competitors for the resource and need external intervention to help build social capability for collective action.
d) Policies and institutions that provide drivers for water conservation and replenishment are lacking.
e) In general there is an awareness of managed aquifer recharge (MAR) among some water users but rarely among water resource managers, and hence a failure to appreciate its complementary role with demand management in sustaining groundwater systems and drought relief. Policies that gain maximum advantage from MAR, identified in TP4, are only emergent and just starting to be adopted in some jurisdictions.
f) Technical capabilities for managed aquifer recharge (site selection, design, construction, operation, maintenance, water quality management) are rarely available within many areas where this suite of techniques would be valuable and economic.
g) There was very sparse information available on case studies of the management of fossil groundwater resources. However one case study was reported.

Key things that decision makers / wider engaged public need to know

Firstly, good groundwater governance is capable of meeting the objectives of maximizing the utility of aquifers while sustaining the environment and providing security for meeting human needs. Many areas where groundwater is a dominant irrigation resource or the main supply for cities are water-stressed and consequently these objectives are not being achieved there. However, in a number of reported local initiatives with public engagement these objectives have been met and deteriorating storages replenished. Best management practice involves quantification of the water resources and formation of plans that account for all resources, groundwater and surface water, including recycling of stormwater and treated sewage effluent where relevant.

If groundwater is not over-allocated, it is easier to manage through a user collective, or to build social capacity for collective action so that this can be formed and manage the resource with technical support from government. Good examples of farmer-led groundwater management are reported in Ilocos Norte, Philippines and in Andhra Pradesh, India.

Where groundwater is over-allocated, and other water resources are available, demand management can be complemented with managed aquifer recharge or alternative sources of water supplied directly (conjunctive use). Implementation of these will require policies and regulations that entrust consultation and establishment of a groundwater allocation plan or sharing agreement with an entity charged with managing the groundwater resource. Transferable entitlements for recharge credits are defined in TP4.

A groundwater allocation plan should be based on a scientific defensible assessment of the available yield of the aquifer and shares in that yield determined for all existing users. No new users would be allowed. The volumetric allocations would be set periodically, say each five years, and any trend in groundwater storage over that interval would be used to revise the allocation for the following period. Allocations should be tradable to allow new entries through purchase of existing allocations.

If groundwater is over-allocated and there are no other water sources available, a groundwater allocation plan would involve demand management, and the primary goal would be to maximize the utility and to prolong the life of the remaining resource through water conservation measures. An exit strategy is warranted and this should be communicated well in advance to avoid wasted investment.

Groundwater as a distributed resource requires participation in management by the stakeholder community. Introducing measurements, such as groundwater level and electrical conductivity, monitoring flow or area of each crop type, rainfall and evaporation, and crop yields would help communicate the link between groundwater system health and the overlying land and water uses.

Most significant prospects and recommendations

Groundwater governance reform in many jurisdictions is warranted. Current unlimited entitlements based on land ownership defy the laws of nature. Inequitable and unachievable entitlements that are currently enshrined in law need to be revised. A new system of entitlements is warranted, based on scientifically defensible methods. Internationally applicable principles for formation of such entitlements are laid out in Thematic Paper 4.

Groundwater resources assessment needs to be quantitative to identify the volumetric allocation from each aquifer, or allocations from different components of each aquifer. In order to pragmatically implement allocations in depleting aquifers, it may be necessary to provide supplementary, temporary, reducing, non-tradable allocations to groundwater users to allow time for adjustment.

Allocations will need to be periodically reset (e.g. say each five years), based on monitoring of groundwater levels and groundwater use. For example, if in parts of the aquifer there is a trend of storage decline, then in that area groundwater users would recognize the need for reducing allocations. TP4 identifies at least ten different forms of demand management methods.

Water resources assessments need to examine all water resources, not just groundwater alone. This will identify opportunities for managed aquifer recharge to replenish aquifers with surface water at times when surface water is allocatable, taking account of environmental flow requirements. Alternatively or additionally, surface waters may be harvested and distributed to replace groundwater use, that is, *conjunctive use*.

Successful management often involves two or three of these elements, with demand management being the highest priority. Increasing recharge or use of surface water sources are unlikely to be successful in restoring groundwater levels unless demand management is also superimposed. A hierarchy of options can be identified based on the relative unit cost of the loss of production from demand reduction, and of implementing managed aquifer recharge or an alternative supply.

Policies that encourage conservation and replenishment of groundwater may be developed that would give greater impetus for private investment in these. For example in Arizona, a *water bank* has been established and developers of new urban subdivisions need to provide 100 years water supply. They do this by going to the water bank to fund the best value project proposed in their area. This will generally consist of a groundwater recharge project using either Central Arizona Project water or local recycled wastewater. In irrigation areas, groundwater users groups may jointly fund the cost of a managed aquifer recharge project in order to avoid a further decline in groundwater allocations.

Capacity building for managed aquifer recharge in much of south and east Asia is limited. Unless water resources managers identify opportunities for managed aquifer recharge and they have access to local technical skills to implement and maintain managed aquifer recharge projects, this prospect for maintaining production at minimum cost cannot be realized. It is recommended that organizations supporting groundwater development and protection, invest in skills development among government and non-government organizations so that managed aquifer recharge projects may be used to sustain groundwater systems. MAR-NET – a UNESCO-IAH initiative – could provide a base for such investment, and network these centres of competence, that each have monitored demonstration projects, to enhance expertise. Managed aquifer recharge stores water from wet periods where it has low or nuisance value, and recovers it for use in peak irrigation season or as a drought and emergency supply at high value. Investment in capacity development will be needed to capture these benefits.

Finally, there is a great deal to be gained by sharing the success stories of effective groundwater governance and the results that have been achieved. These give confidence that groundwater is manageable using a variety of methods adapted to the local situation through participation by stakeholders. Some training may be needed for water resources managers in engaging with communities to help them recognize the problem they share in common and identify solutions that require collective effort to achieve their objectives. Particular help may be required where there are existing nonviable legal entitlements and where fossil groundwater is being used.

Thematic Paper 4

MANAGEMENT OF AQUIFER RECHARGE AND DISCHARGE PROCESSES AND AQUIFER STORAGE EQUILIBRIUM

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Appendices

Executive Summary

This Thematic Paper reviews the state of management of groundwater recharge, discharge and storage in relation to physical, institutional and social factors.

In the three countries with the highest rates of groundwater overdraft, storage declines are accelerating and expose the widespread failure of current groundwater management strategies that are based on the concept of private ownership of groundwater.

However, elsewhere there are numerous proven effective management strategies based on the concept of groundwater being a common pool resource. This thematic paper draws attention to case studies from a range of hydrogeological, climatic and societal settings where innovative management has been conspicuously successful in reversing groundwater storage declines (or increases).

A combination of three elements; demand management, recharge enhancement and alternative supplies, can sustain or prolong groundwater resources and maximize the value of their utilisation. Embedded within an integrated natural resources management framework, these elements can also enhance agricultural livelihoods and social cohesion and restore water quality and degraded environments. At each location, the balance between these major elements and the selection of methods depends on the availability and cost of surface water resources (natural, stormwater, recycled water), on the economics and capabilities for managed aquifer recharge and on the economics of improving irrigation efficiency and foregoing production.

It is recognized that in the absence of adequate surface water resources, and low rates of replenishment there may be an intentional policy of mining groundwater for irrigation as a transitional pathway to a less water-dependent economy.

Instruments such as setting entitlements, volumetric allocations and use conditions, assist with demand management and allow trading to maximize the utility of the groundwater resource.

In some cases new institutions such as catchment water management boards, water banks and water user associations may assist in implementing and sustaining reforms.

Informing and engaging stakeholders in governance has resulted in more resilient outcomes that take better account of local needs.

Importantly, in many settings local action by motivated communities has run ahead of state and national policies and has been highly effective in managing groundwater storage, increasing farm incomes and protecting the environment. Clearly, where there are also supportive government policies, local reform is easier to implement.

The paper concludes with a unifying synthesis of pathways through policy reform, based on integrated water resources assessment, and including evaluation of groundwater stress, community capabilities for collective action and the availability of other water resources.

In summary, there are many good news stories about over-allocated aquifers that have been restored to hydrologic equilibrium by a variety of means, and it is hoped that this document will raise awareness of viable alternatives to currently doomed conventional strategies.

2. Introduction

The purpose of this GEF Project Thematic Paper is to review the state of management of groundwater recharge, discharge and storage in relation to physical, institutional or social factors. This is one of a series of Thematic Papers to diagnose historical and current issues and examine examples and prospects of regaining aquifer integrity and function or mitigating further impacts through improved water governance. The paper is intended to illustrate how global benefits can accrue through fresh and unified approaches to groundwater resource management that will halt or retard aquifer storage and water quality declines and the consequences of the loss of the state of equilibrium.

The scope of this paper is at a macro-view level while using localized case studies to illustrate the effectiveness of various strategies and the circumstances that influence success. The paper starts with a summary of current practice and the consequences. This baseline reveals that business as usual is already having serious repercussions, and new strategies are necessary. Next, various problem typologies are diagnosed and hierarchy of potential governance solutions proposed. In some cases there are outstanding current examples of historically intractable problems having been overcome, offering confidence to groundwater managers around the globe facing similar situations. Finally, a hierarchy of implementation strategies for innovative policies is suggested, assimilating outcomes of case studies.

This document was prepared by World Wide Ground Water through a team from the International Association of Hydrogeologists Commission on Managing Aquifer Recharge with the support of CSIRO Water for a Healthy Country Flagship Program.

2. The state of groundwater governance in relation to the recharge and discharge processes and aquifer equilibrium states *'(Baseline)'*

2.1 The status of groundwater storage

Groundwater storage is shown to be declining in all populated continents, and the global depletion rate over 2001-2008 was estimated by Konikow (2011) using a variety of methods, but notably including groundwater level changes, as 145 km^3/yr (equivalent to 0,40 mm/yr of sea-level rise or 13% of current rate of rise). This is largely the result of increased abstraction through the advent of electric powered pumps and improved drilling techniques making groundwater more accessible in larger volumes and from greater depths. Contemporary climate change causing changes in recharge has had a very much smaller impact on storage (Kundzewicz *et al.*, 2007).

Konikow estimated the cumulative global groundwater depletion from 1900 to 2008 as 4 500 km^3 (Figure 1 from Konikow, 2011). An alarming feature of this graph is the continuing acceleration in rate of groundwater depletion. Starting from an almost negligible decline until 1950 the rate of depletion between 1950 and 2000 was doubled in the period 2000 to 2008. The fastest decline has been largely focused in irrigation areas of semi-arid and arid countries, with northern India and United States sharing responsibility for more than half of the overall global depletion. Other significant declines have been observed in Saudi Arabia, the North China Plain, the Nubian Aquifer System and the North Western Sahara Aquifer System. In most of those areas current groundwater recharge is negligible in comparison with extraction and water resources managers regard groundwater as a non-renewable resource. A further 30% of the total estimated depletion is from systems in other countries that were not quantitatively evaluated.

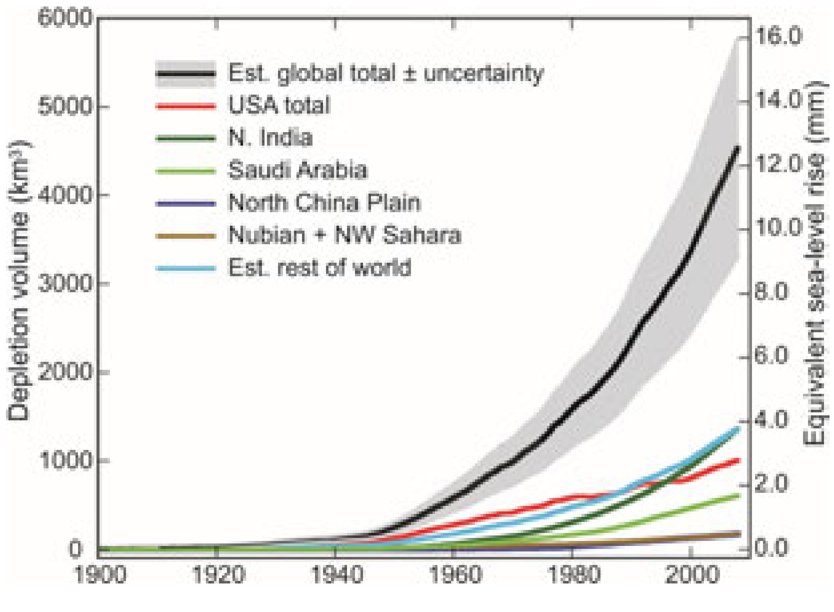


Figure 1. Estimated cumulative global groundwater depletion (1900-2008) (from Konikow, 2011, used with permission).

Comparing these figures with estimates by Margat (2008) of annual exploitation of groundwater of 800 km^3/yr suggests that storage decline is only an aggregated 18% of groundwater extraction. In shallow systems this may be in part be due to induced additional recharge, for example as observed in Tamil Nadu, India, by Charalambous and Garratt (2009). In general, if return flows to aquifers from irrigation were of the order of 20% of extraction, in systems that are drawn down so that water table no longer influences the recharge volume, then the net decline in natural groundwater discharge would be about 500 km^3/yr. This means that the impacts on surface water resources and groundwater-dependent ecosystems of groundwater extraction may be much more significant than revealed by the observed change in groundwater storage. While groundwater in places is a relic reservoir resulting from former wetter climates, in many places it is a dynamic flowing system. Global mean natural recharge exceeds 12 000 km^3/yr (Margat, 2008) (out of 106 000 km^3/yr precipitation on land; UNESCO and Earthscan, 2009) and was on average balanced by natural discharge prior to extraction by man. That is, exploitation of only 7% of global natural recharge is sufficient to cause the observed significant storage decline, and related effects on surface water resources and groundwater-dependent ecosystems.

Global figures reveal the significance of the storage change issue but the magnitude, causes, consequences and management responses vary enormously among regions. In many places groundwater use is low or sustainable without adverse consequences. The various regions where declines are emergent or significant cover spectra of socio-economic conditions, replenishment and extraction rates. Several typologies will be discussed later.

Consequences of ongoing decline in groundwater storage are (Burke and Moench, 2000):

- deterioration of groundwater dependent ecosystems and depletion of surface water resources;
- higher pumping costs, energy consumption and greenhouse gas release;
- need to deepen wells to maintain supplies, and in general only the wealthiest will be able to pursue the falling water level and we have *the tragedy of the commons*;
- deterioration of groundwater quality, due to upwelling in stratified aquifers or saline intrusion from brackish groundwater or from the sea in coastal aquifers;
- land subsidence where aquifers are confined and aquitards contain clays that are compressible when pore pressures drop (reviewed by Galloway and Burbey, 2011);
- competition for scarce groundwater resources among and between sectors of the economy causing social and political stresses;
- reduced incomes for farmers and industries previously reliant on groundwater;
- migration to cities and closure of services in rural areas as a result of income decline;
- uncertainty in communities concerning their future viability and loss of cohesion.

On the other hand, consequences of not exploiting non-renewable groundwater resources include denial of the opportunity to current generations for development, increased income, improved health and establishment of more stable human settlements and industries than could otherwise exist. It has been argued that if each generation prohibits mining of a given resource in order to conserve it for future generations then no generation will receive the benefit of that resource (Barnett *et al.*, 2010) and little thought is given to preserving other non-renewable resources such as oil, gas and minerals for future generations. However, in deciding to exploit such a resource, the consequences of progressive decline in storage and natural discharge, outlined above, need to be taken into account, and plans must be developed and communicated to address the consequences.

Globally, 70% of all water withdrawn from aquifers, lakes and streams is for agricultural production, and the Food and Agriculture Organization of the United Nations (2011) predicted that by 2050 there will need to be 70% more food production globally to sustain the growing population and hence a need for much more effective policies for land and water management. Not only is demand increasing, but rainfall and recharge to groundwater is expected to decline in many semi-arid areas that depend on groundwater for irrigation (Kundzewicz *et al.*, 2007).

Notwithstanding the global storage decline, in some areas groundwater levels are rising causing water-logging or soil salinization problems. Examples include areas where surface water irrigation occurs and the rate of groundwater mound dissipation is slower than the groundwater accession rate beneath the irrigation area. Conjunctive use of surface water and groundwater is proposed as an effective management strategy in such areas, as for instance in a number of canal-fed irrigation developments in India (e.g. Uttar Pradesh) where substitution of groundwater for some supplies has restored groundwater levels. Garduño *et al.* (2011) report the case of Uttar Pradesh in the Ganges alluvial plain where 50% of the area is suffering groundwater decline due to intensive irrigation and 20% is threatened by a rising shallow water table in the vicinity of surface-water irrigation canals. In these areas a conjunctive use approach that includes reducing seepage from leaky channels, improving canal operations, encouraging tube wells in high water-table areas for groundwater irrigation, and investing in soil salinity and sodicity mitigation is implemented. This is anticipated to increase cropping intensity through reducing sodic land problems while sustaining groundwater.

In areas where land use change has been extensive, such as clearing of forest or other deep-rooted perennial vegetation, increased recharge due to lower evapotranspiration may raise the water table and cause water-logging in humid areas or soil salinization in semi-arid areas. In land with low topographic relief and extensive aquifers it is clear that no individual farmer acting alone could solve the problem. Land Care – a grass-roots collective movement among Australian farmers, agricultural researchers and extension officers – has been highly effective in identifying natural resources management problems, building capability to select and implement solutions, including revegetation, and to monitor changes in groundwater levels, ecosystem health, biodiversity and agricultural productivity in an adaptive community-wide approach (Government of Australia, Department of Agriculture, Fisheries and Forestry 2008). Actions by Land Care Groups are generally resourced by group members and competitive government natural resources management grants. A national awards programme recognizes the most conspicuous achievements.

2.2 Groundwater management objectives

Objectives for groundwater management relate to maximizing economic utility of aquifers while sustaining the environment and providing security for meeting human needs (Figure 2). This simple statement reveals the crux of the groundwater management issue. Utility or value of groundwater use varies with time depending on the time series of annual or seasonal volume of water recovered, and the unit contemporary economic and social value of the uses of that water. Managing groundwater to maximize utility therefore depends on the discount rate used to value future uses. In some arid areas, groundwater irrigation at unsustainable rates has been part of an intentional plan to help rural populations to transition to an economy that is less water-dependent (Moench *et al.*, 2005).

In its simplest form, maximizing utility over the time period of one or two electoral cycles and disregarding future values would always lead to resource depletion. If groundwater resource levels and ecosystem and economic functions are to be preserved so that the aquifer can continue to be used by future generations, then a very low discount rate should be used for decision-making about temporal patterns of abstraction. It is also evident that where the aquifer is only used for the highest-valued uses, the economic utility of groundwater use will be maximized. Therefore, it is possible that reducing abstraction for lower-valued uses can increase the utility of groundwater use. This model also implies the value of collective management of all abstraction from the aquifer. Where there is no constraint on volume or type (value) of use, the utility of the resource will be smaller than where management is effective. The costs of management are presumed to be small with respect to the consequent increase in utility for the community, as revealed by numerous case studies (e.g. Foster *et al.*, 2011).

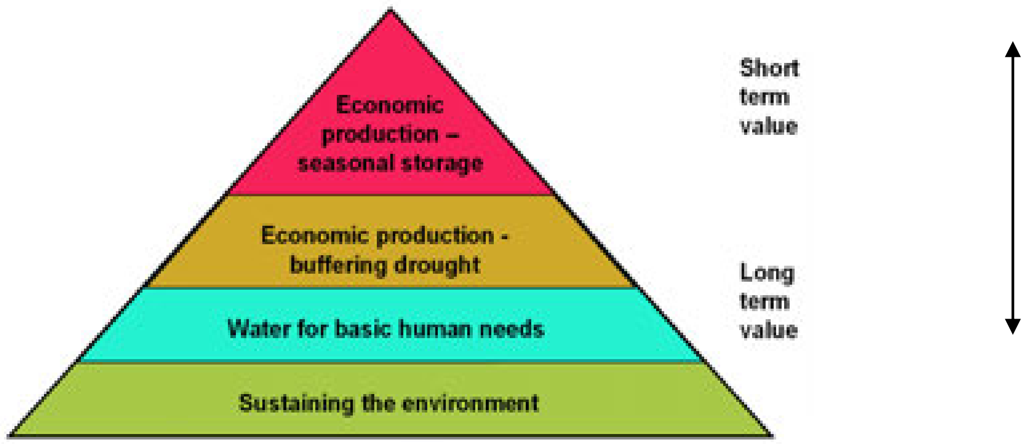


Figure 2. Aquifers have a range of attributes for which they are valued.
Consideration of irrigated agricultural production needs to first take account of other more enduring and potentially more valuable functions, in addition to a holistic view of the availability and function of other potential sources of water.

Groundwater mining is a strategy where current resource use for economic gain takes precedence over not only potential future uses, but also over immediate impacts on groundwater dependent ecosystems. This strategy should also take account of the decline in flow in any connected surface-water system, with consequences to water users reliant on those systems. Transitional arrangements may include switching from groundwater supplies to new alternative supplies. Already treated sewage effluent can be economic as a substitute water source, such as in the vicinity of Mexico City. However, care is needed to ensure groundwater quality protection through adequate treatment and informed irrigation management. To date, and for the foreseeable future, the cost and energy requirements of seawater desalination are likely to be prohibitive for crop irrigation.

An overarching integrated water management framework, where groundwater is one of the sources to meet the range of uses, taking into account the quality being fit for purpose, suggests that optimal utility of integrated water management will exceed that for managing groundwater independently. Furthermore, the characteristics of groundwater storages can be a major advantage when integrated with other systems. For example, groundwater may be most valuable as a drought and emergency supply, taking account of its reliability, protection from evaporative losses and consistency of water quality in comparison to surface water sources. Hence, integrated management, in some cases will be most efficient through interventions to replenish groundwater in periods of excess surface water availability. This practice, known as managing aquifer recharge, has to date been used largely by groundwater users to augment groundwater resources, but has rarely been considered by water resources managers as part of an integrated water management strategy.

2.3 Conventional groundwater management methods

Evidently, in general, our current models for groundwater governance are unsuccessful in restricting groundwater depletion and also fail to stop the accelerating rate of depletion. Either the current benefits of groundwater overexploitation are seen as outweighing the current and future costs of depletion, or else governance processes are failing to observe the status of systems, develop effective plans, engage with communities and stakeholders, implement reform or adopt combinations of these measures.

Practices commonly applied involve groundwater resource assessment and demand management (Box 1). There is no substitute for having adequate scientific assessment of groundwater resources (e.g. Pavelic *et al.*, 2011; water balance studies in West Africa). However, resource assessment is often initiated after it is appreciated that there is a problem with falling water levels. This means that there is entrenched investment in groundwater use that exceeds long-term supply and creates environmental detriment. This makes demand management problematic. Hence, resource assessment at an early stage with dissemination of information would be an important step forward as a preventive measure (Figure 3).

Demand management can take many forms. The simplest is ***laisser-faire*** management or “let the aquifer decide”. Groundwater users take whatever they can from a depleting aquifer, leading to intermittent and inadequate supplies, high groundwater pumping costs and wasted investment if the crop cannot be brought to maturity or industry closes. High valued uses such as drinking water supplies may be denied to sectors of the community who lose access to groundwater for lower valued uses. Demand will shrink to those who can afford to extract groundwater. The decline will be disorderly, disruptive, divisive and painful for many.

Improved water-use efficiency can also be an important part of reducing demand, if this does not also result in expansion of irrigation areas. More ‘crop per drop’ can also be achieved through improved agricultural knowledge and practices, including mulching and fertility, giving consideration to crop selection, timing of planting, improved irrigation methods, and discontinuing irrigation on soils that are unsuitable. These can potentially increase farm revenue while reducing groundwater consumption. Motivation can also involve water or energy pricing to discourage profligate use and to reflect actual costs of supply.

Systems where **entitlement to ground water is linked to land ownership** have very similar consequences to *laisser-faire* management. While land ownership gives a very simple system of rights there is no assurance that supply can be sustained at the capacity of the land for growing crops. In fact in semi-arid areas it is highly likely that extraction would exceed all recharge through the land surface of the property. Furthermore, some or all of that recharge would previously have contributed to groundwater discharge to streams and groundwater-dependent ecosystems. So even constraining the right of the landholder to extract all recharge from their property would ensure environmental degradation.

Box 1. Elements of effective groundwater management plans

Resource assessment

- Require drillers to have training and adhere to standards (licensing drillers)
- Require geological or drillers logs, yields, water samples and water levels of all new bores to be recorded and submitted to a government database
- Install observation wells to help reveal the initial status of the resource in locations where groundwater use is likely to increase
- Record groundwater levels and groundwater quality in observation wells
- Record estimated aggregate use from existing wells
- Record status of springs and groundwater dependent wetlands
- Groundwater resource assessment to estimate natural recharge and discharge and impacts of various future levels of exploitation.

Demand management

- Improve irrigation efficiency
- Select crops with lower water requirements
- Pricing of electricity or water should reflect costs of supply and encourage conservation
- Restrict proximity of new wells to existing wells and groundwater *aflaj* (reducing interference)
- Restrict proximity of wells to environmentally sensitive natural groundwater discharge zones with high conservation value
- Restrict depth of wells (used to self-constrain extraction) for various types of wells, (e.g. drinking water supply wells may be deeper than irrigation wells)
- Record crop areas and restrict the maximum area of crops irrigated by a well
- Fit cumulative flow meters to wells and monitor
- Periodic revision of groundwater resource assessment informed by monitoring data, groundwater use information and further hydrogeological investigations
- Prepare a groundwater resources allocation plan for community consultation
- Farmer-led groundwater management (generally where systems are not already over-exploited)
- Assign groundwater entitlements as shares in the resource, subject to conditions of use
- Allocate groundwater extraction constraints with compliance monitoring
- Develop groundwater trading arrangements for entitlements and allocations
- Periodically revise plans and allocations.

Groundwater replenishment (managed aquifer recharge) or supply substitution

- Identify and test options for enhancing groundwater recharge and evaluate alternative supply options for recharge or to replace groundwater use
- Include provision of managed aquifer recharge and alternative supplies in groundwater resources allocation plan for community consultation
- Assign groundwater recharge entitlements as shares in the replenishable volume, subject to operating conditions
- Assign recharge recovery allocation rule (to the environment or to groundwater users based on recharge operations and who invested)
- Build, operate and monitor managed aquifer recharge projects, resourced through sale of recharge recovery allocations or through government support of groundwater management
- Maintain records for recharge credit allocations
- Periodically review rules and performance as part of the water allocation plan for community consultation.

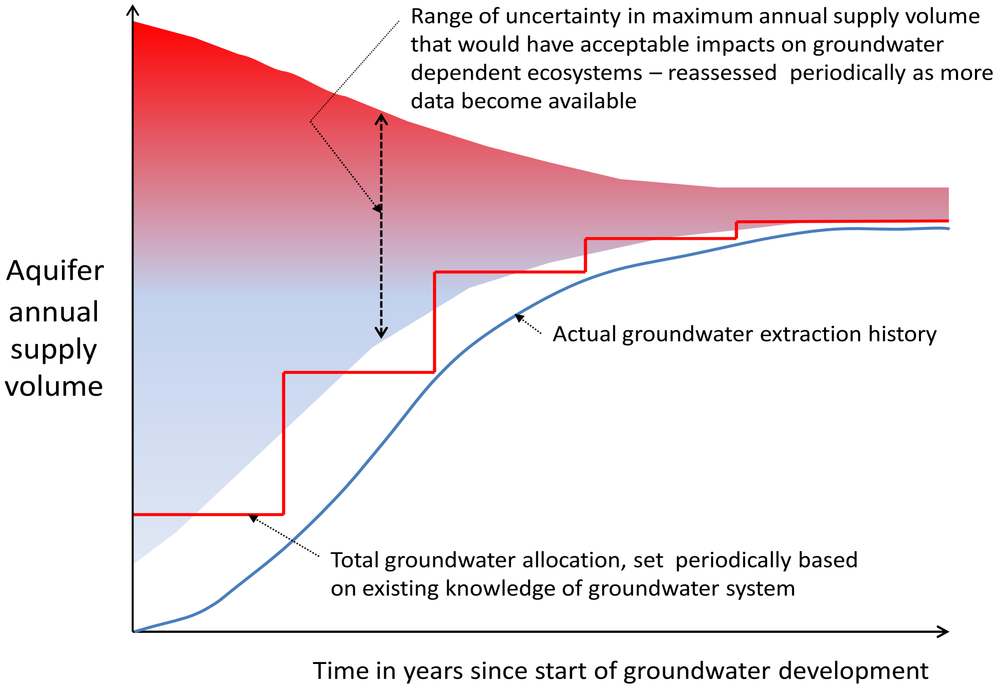


Figure 3. Groundwater resource assessment at an early stage may be crude but it does provide a basis to establish a groundwater allocation system to avoid over-exploitation.

As more information becomes available during groundwater development the uncertainty in aquifer response reduces and groundwater allocations are periodically adjusted. Upward adjustments are very easy to accommodate, however downward adjustments are difficult. Hence, initially conservative resource allocations would be wise.

In addition, evaporative concentration of solutes in applied water would result in chronic groundwater quality deterioration. Furthermore, there is no assurance that water use will be for the highest-valued uses, especially where soils are variable and support different crops with quite different economic returns per unit volume of water irrigated. The concept of a groundwater system being divided into fenced parcels with independent ownership is as absurd as the notion that a landholder would own migratory birds that rested on their property.

Entitlements have also been allocated in the order of sequence of exploitation, that is, a **prior-rights system**. However, this also entices over-exploitation. An astute land-holder aware of the value of groundwater would logically aim to be first to create wealth through as much irrigation as possible in order to have established a prior right to that volume of water. As soon as neighbours see the benefits of groundwater use, there is a race for groundwater consumption to secure entitlement. Subsequently, when the system is clearly over-allocated, the last users are denied an entitlement to extract groundwater and the resource allocation is monopolized by earliest users. As with land-tied water entitlements, this constrains the utility of the aquifer whilst ensuring inequitable allocations. Prior use systems have been well intentioned to protect rights of Native American Indians in some States of USA, but rarely do they account for environmental uses of groundwater, such as ecosystem support. Supplemental measures, such as early groundwater laws in Nebraska in 1957, covered the registration of irrigation wells and set a minimum well spacing of 200m to reduce conflicts between groundwater users.

A **centralized system of consumption constraints** has also been attempted in a number of places. This is when a government authority defines the total allowable volume of water consumption and then applies this by pro-rata, or some other method to assign allocations to individual users. This can be accompanied by compulsory installation of meters on wells, or by regular survey of the area under crop to determine compliance. Such non-consultative attempts to constrain groundwater use have resulted in poor levels of compliance, penalties for farmers, expensive monitoring and litigation, increasingly complicated governance arrangements (e.g. accounting for carry-over of unused allocations), a perpetual chasm between groundwater regulators and groundwater users, and conflicts between users. A combative approach means future adjustments to allocation are also met with resistance and groundwater management becomes politically charged.

In relation to the regions where groundwater storage decline are greatest, Table 1 gives a view of storage decline (Konikow, 2011) and relates these to the dominant groundwater entitlement systems applied and their projected capability to manage depletion. Irrigation is the dominant groundwater use in every case. In essence, Table 1 confirms that groundwater title that is attached to land ownership is a failed experiment and needs to be abandoned in favour of more innovative approaches that are described below.

Table 1. Dominant groundwater entitlement systems and groundwater uses in relation to groundwater storage decline

Region	Mean annual storage decline 2000-2008 (km^3 / yr)	Dominant groundwater entitlement system based on:	Current groundwater storage projections	Dominant groundwater use
USA	25,5*	Land ownership or prior rights	Depletion	Irrigation
Northern India	52,9*	Land ownership	Depletion	Irrigation
Saudi Arabia	13,6*	Land ownership	Depletion	Irrigation
North China Plain	5,0*	State ownership but licensing ranges from comprehensive to effectively unlicensed	Sustained production to depletion	Irrigation
Nubian Aquifer	2,4*	Land ownership	Depletion	Irrigation and city supplies
NW Sahara	2,2*	Land ownership	Depletion	Irrigation
Australia	<0,3**	State ownership and water access entitlement	Sustained production	Irrigation, stock and domestic supply
Philippines	<0,1**	Shared use of common pool resource	Sustained production	Irrigation

* from Konikow (2011); ** estimated

2.4 Innovative groundwater management methods

However there is good news. There is an increasing variety of groundwater governance methods including cap-and-trade systems, managed aquifer recharge and substitutional supplies that provide groundwater managers many more degrees of freedom in order to bring groundwater systems into equilibrium while minimizing costs or even increasing production. There are also excellent examples of communities with groundwater systems in decline who have implemented effective strategies and have reversed groundwater depletion and re-established desired equilibrium conditions.

Community engagement and building institutional capacity allow holistic solutions tailored around community needs (Moench *et al.*, 2005). Such interventions generally address multiple connected issues, such as health, livelihoods, environment, and in acting to resolve shared groundwater problems, community cohesion and wellbeing are enhanced. Technical capabilities to assess hydrologic balance, improve irrigation efficiency and crop selection, enhance groundwater recharge or develop substitute supplies will be required. Importantly institutional capabilities to influence supply and extraction, to build and maintain infrastructure and to finance such activities are also necessary and generally evolve from existing community cooperative arrangements and structures (Wegerich, 2005).

The ongoing good news is that these actions can occur at decentralized level by motivated communities, with technical support, without necessarily waiting for national or state policy reform, although this would certainly expedite more broad-spread effective action and make technical expertise more accessible. There are many outstanding examples of localized collective actions to resolve issues with reducing and insecure supplies (e.g. Government of India, Ministry of Water Resources, 2012b and Garduño *et al.*, 2011). A selection of examples is summarized in section 3.

As an introduction to additional innovative strategies, a brief description of the state of the art in groundwater allocation (demand management), groundwater recharge enhancement and substitutional supplies is given below, with examples provided in Section 3.

A **decentralized system of entitlements and allocations** has been employed in recent years in various jurisdictions. This involves determining the total volume of groundwater extraction considered acceptable or sustainable. A water allocation plan is then devised in partnership with the community to determine the proportion of this volume to which each groundwater user may have an entitlement. That is like shares in a stock-market and if the volume deemed to be available for allocation is adjusted, based on a scientific assessment, the volumetric allocation is automatically determined based on the predefined entitlement share. The distinguishing feature is that entitlements are awarded on the basis of community support on the method of allocating shares and that shares are then allocated in a defensible way. This may require, at the community's request, measurements via meters or land use maps and satellite imagery. It is important to note the separation of processes between determining shares or entitlements and determining allocations (Young and McColl, 2003). That is the contemporary volumetric allocation is based on the individual's defined share in the resource and the latest scientific assessment of the volume available for allocation. Note that while this method overcomes the fractious nature of centralized allocations, but on its own it does not ensure that water is used for the highest-valued uses.

Where excess surface water resources are available, even intermittently, it may be more economic to recharge groundwater than to forego already efficient irrigation production. **Managed Aquifer Recharge –** is the term describing the increase in groundwater recharge over what would have occurred naturally, as a result of interventions designed to enhance groundwater storage and quality. That is, groundwater managers can evaluate supply-side as well as demand-side options. In some locations, it may be more efficient to replace groundwater supplies with a surface water distribution system to reduce demand on groundwater. That is **substitutional supplies** may be an effective way of meeting the need for irrigated food production while sustaining groundwater. Conjunctive use of groundwater and surface water may be helpful in preventing water-logging in surface water irrigation areas.

3. Elements contributing to successful management of groundwater storage

Innovative methods for groundwater management to complement and augment or replace traditional methods include a more flexible approach to demand management, as farmer led management (for aquifers that are in storage equilibrium), a cap-and-trade system, and supply-side measures of managed aquifer recharge and substitutional supplies. These are described in turn below and illustrated by examples in the Boxes 2 through 14.

3.1 Management by groundwater user collectives

In aquifer systems that are not over-allocated the management options expand greatly, and the tension in implementing them is low. Farmer-led management, such as in the northern Philippines (Dillon *et al*., 2009b) has been implemented with technical support and training by the Philippines Bureau of Soil and Water Management in two communities overlying coastal aquifers where groundwater use for irrigation has been expanding. The programme has been highly successful, leading to improved crop selection related to soils, improved irrigation efficiency, increased yields, community-based groundwater monitoring and evaluation and collective decision-making concerning crop planning taking account of the status of groundwater storage; and greater knowledge of the aquifer, the consequences of excessive use, and implementation of well-head and groundwater-quality protection measures concerning fertilizers and wastes. Farmer Water Management Schools provide an effective model that can be extended to other groundwater irrigation areas.

Box 2. Curriculum of Farmer Water Management School, Llocos Norte, The Philippines

Module 1	Knowing weather and climate as an important tool to develop cropping pattern and calendar
Module 2	Operation and maintenance of pump and engine sets
Module 3	Soil management
Module 4	Hydrologic cycle and understanding groundwater supply
Module 5	Groundwater movement and quantity
Module 6	Groundwater quality and contamination
Module 7	Groundwater balance (recharge and discharge)
Module 8	Introduction to crop planning
Module 9	Integrating groundwater balance and crop planning
Action planning session	
Exhibition & graduation	

Source: Philippines Bureau of Soil and Water Management

(a) (b) (c)

Farmer water management school activities at Pasuquin, Philippines: (a) Pump operation and measurement of discharge; (b) Field day and exhibition stations manned by FWMS farmers; (c) Recording monthly rainfalls and groundwater levels. (photos by Samuel Contreras, Philippines Bureau of Soil and Water Management).

Box 3. Andhra Pradesh Farmer-Managed Groundwater Systems, India

Andhra Pradesh Farmer-Managed Groundwater Systems (APFaMGS) was an FAO supported project aimed at improving the water use efficiency by empowering farmers in monitoring and managing groundwater resources in their hydrological unit. The project developed people's institutions for groundwater management, augmentation of groundwater resources through recharge enhancement and promotion of sustainable agricultural practices. It was conducted in the State of Andhra Pradesh, in southern India, and spread over 638 villages in seven drought prone districts.

More details of the methods and achievements of this project which focused on empowering self-imposed demand management supplemented with recharge enhancement where warranted are at http://www.fao.org/nr/water/apfarms/index.htm.

Measuring and recording hydrological variables. The project subtitle was "Demystifying science for sustainable development".

Box 4. Integrated natural resources management at village level in a drought-prone area (adapted from Garduño *et al.,* 2011, and Government of India, Ministry of Water Resources, 2012b)

Hivre Bazaar is a village of 1 200 people in a semi-arid (450 mm/yr average rainfall) and drought-prone elevated part of the Deccan Traps Basalt of Maharashtra, in western India. Agriculture is the mainstay of the economy, with staple crops grown for home consumption or used as livestock fodder or domestic fuel, while most pulses, onions, vegetables and flowers are sold at the market. Up to 60% of land can be irrigated in years with good monsoonal rainfall but in the 1989/90 drought this fell to less than 5% and all village wells ran dry.

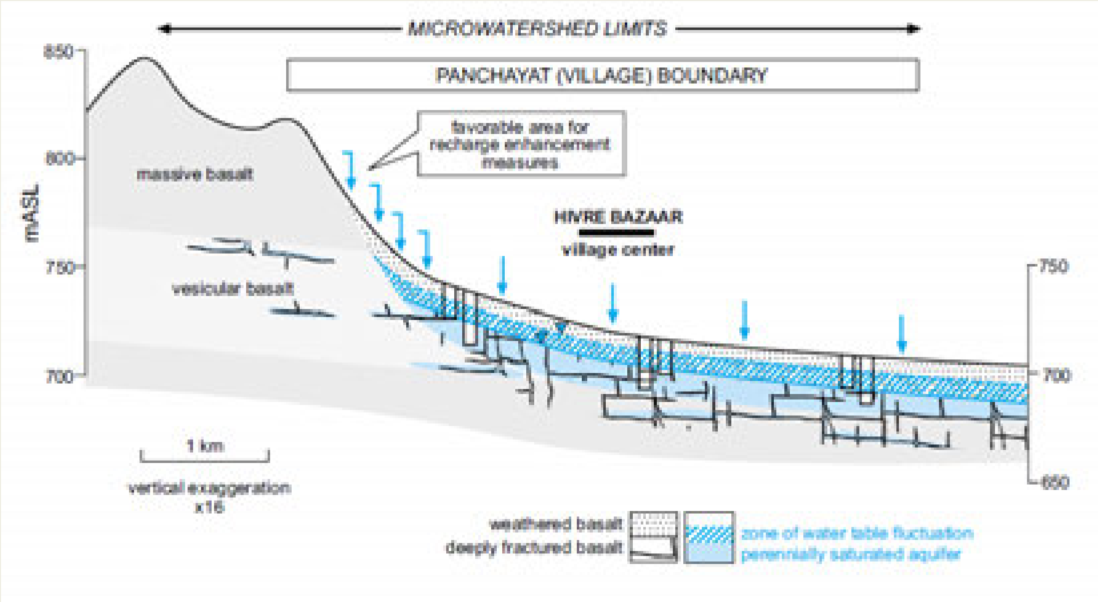
Led by an informed and charismatic Village Council Chief, a concerted effort on catchment and groundwater management and agricultural reform began in 1994. The Village Council acted to:

(i) prohibit the use of tube wells for agricultural irrigation,
(ii) implement micro-watershed soil and water conservation, and
(iii) ban sugar-cane cultivation.

These measures, implemented in a comprehensive 5-year plan, had the effect of diverting farmers' resources away from unproductive competition for scarce deeper groundwater water to water conservation and recharge enhancement for the shallow (up to 15 m below ground surface) weathered-zone aquifer. Extensive effort went into hill contour trenching and stream bunds. Reforestation assisted by a livestock grazing ban restored degraded land, reduced erosion, improved the quality of water and reduced low-valued irrigation requirements. Sugar cane had high water-use, and banning its growth, also eliminating distilling practices and socially undesirable consequences, improved crop selection and maximized the value of irrigated crops.

Village-level crop-water budgeting was introduced in 2002 and in dry years villagers are asked to reduce their proposed irrigated area and to give preference to low-water demand crops. Mutual surveillance is usually sufficient to achieve compliance. Such proactive groundwater and agricultural management has resulted in a marked contrast between Hivre Bazar and most surrounding villages.

The consequences were remarkable. Household incomes rose markedly (to over US$500 per year on average), and land values appreciated many-fold in the past 15 years. Drought resilience and income security has increased and farmers no longer need to leave the village to search for paid work in dry years. Degraded land has been restored and made productive. As many as 32 dug wells produce important revenue in the dry season from irrigated onion, vegetable and flower cultivation, and only a few in the upper watershed dry out.



Simplified hydro geological section of Hivre Bazaar micro-watershed methodology of study (from GW-MATE, 2009)

Hivre Bazaar (a) catchment before intervention, (b) a percolation tank for aquifer recharge, (c) consequent productive irrigated agriculture. (*Sources from various Hivre Bazaar websites*).

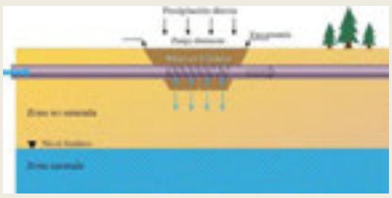
Box 5. Example of management by groundwater user collectives in Spain

Since the mid-20th century the expansion of irrigation from "Los Arenales" aquifer, located in Castilla y León, Spain, has led to decline in groundwater level of more than 20 m. The Aeolian sand aquifer, with an area of 1 500 km^2 and thickness up to 55 m is also very vulnerable to drought (MAPA, 1999). In order to mitigate this impact, the Spanish Ministry of Agriculture (MAPA) developed Managed Aquifer Recharge (MAR) facilities in three pilot zones. These were accompanied by improvements in water management, based on the organization of communities of irrigators, exchanges of arable land, changes in crops, improved efficiency of irrigation and reduction of energy consumption. Also there was recovery of environmental features such as degraded wetlands (La Iglesia and El Señor lagoons), springs that had dried and dilution of nitrates and of other pollution.

River water was diverted for recharge (respecting evaluated ecological flow) by gravitational flow through 18 km of buried pipes to the recharge facilities, including infiltration ponds, artificial wetlands, canals and large diameter wells. Some years later, researchers successfully tested buried filter pipes and drainage ditches (Fernandez, 2010a). Once constructed and commissioned, the works were transferred to the communities of irrigators, who are responsible for the management and maintenance, under the advice of specialists of the Duero Hydrographic Confederation (CHD). Due to variable river flows annual volumes recharged in the two main experimental pilots ranged between 0.5 and 12.2 Mm^3 (Santiuste basin) and between 0.5 and 5.5 Mm^3 (Carracillo council) between 2002 and 2008. The river water was supplemented by 0.5 Mm^3/year treated sewage effluent since 2005.

Initially some farmers resisted the new organizational structures and this was resolved through negotiation. DINA-MAR implemented "The Water Ways", a process of informing the community on sustainable development, environmental awareness and hydrogeological processes, including applications of Managed Aquifer Recharge (Fernández, 2010b). Subsequently there has been an unintended increase of about 15% in the irrigated area due to what has been called "contagious effect", of a decline in the price of water and in the costs of pumping. Incipient economic resurgence is observed in these rural areas that had previously been depressed. Of concern is the growing demand for irrigation supplies in areas where MAR is not feasible or not recommended. Innovative approaches will be needed to achieve collective solutions to these problems.

This experience is a significant example of public participation, first as the trigger that stimulated the construction of MAR facilities by the Spanish Government and, importantly, as groundwater users increased their productivity and water management efficiency. This also demonstrates integration of recharge enhancement with demand management. There is also a new shared perspective of the aquifer both as a resource for irrigation and for sustaining the environment. Organizational change has motivated a substantial environmental improvement and will provide a basis for resolving emerging issues.



(a) Diagram of recharge basin on pipeline from river that recharges groundwater

(b) Water from wastewater treatment entering recharge ditch

(c) Water replenishing wetland

Box 6. Example of agronomic water conservation measures in central Punjab (adapted from Garduño *et al.*, 2011)

In Punjab 70% of the irrigated area is dependent on groundwater delivered by 2.3 million farm tube wells with electric submersible pumps. Rice growing was resulting in groundwater net deficits of 120-180 mm/year. Groundwater tables were falling at 0.6 to 1 m/yr, many wells were being deepened and the State government was underwriting soaring energy costs.

In response, in 2008 the State government issued an ordinance prohibiting transplanting of paddy rice until June 10, the start of the monsoon, and up to 40 days later than the usual practice. This eliminated an estimated 90mm of non-beneficial evaporation and 175 million KWh electricity consumption without impacting on crop yields.

This was highly successful, with more than 95% farmers compliant because violations were highly visible and severely penalized. Additional measures were incorporated in the Punjab Preservation of Sub-Soil Water Act of 2009, including laser levelling of fields, soil-moisture-based irrigation timing for winter wheat, and improved faster growing rice varieties to minimize irrigation requirements. Water level responses are being monitored to determine the impacts of these policy changes, which are expected to prolong the groundwater resource by reducing the deficit by 50 to 65%.

3.2 Cap and trade demand management

Cap and trade systems are designed to allow exchange of entitlements and/or allocations among groundwater users, including new entries. Trading systems are set up to allow water to be transferred from lower- to higher-valued uses, subject to environmental conditions. This increases the utility of the aquifer. The user with a higher-valued use of groundwater can afford to buy an entitlement (long-term share) or an allocation (volume of water in the current water accounting period) from a user who may receive more for their allocation than they would from the net return on the crop they could grow on their soils with their resources. Hence, this can be a win-win situation, where both parties and the community at large benefit from the reallocation of the resource. Constraints on trade may include that allocations cannot be traded further down-gradient in established groundwater cones of depression, or towards groundwater dependent ecosystems or hydraulically connected streams. There may also be constraints on exchanging fresher groundwater for more saline groundwater as the average salinity of the aquifer may increase. Also, consideration would need to be given to preventing the trade of 'sleeper' entitlements (entitlements held on paper but not actually used), as otherwise groundwater extraction from the aquifer would actually increase. A cap and trade approach also gives the government the option of buying entitlements on the water market on behalf of the environment.

Cap and trade systems can be used with any prior entitlement allocation system that is over-allocated. A volumetric discount may be assigned to the traded allocation so that the aquifer could potentially reach hydraulic equilibrium through groundwater trading. The traded allocation would of course need to be divorced from any land or prior rights. Allowing trading could also be accompanied by substitution of shares in the allocatable pool to replace volumetric allocations to all groundwater users, as a way of addressing the longer-term needs for sustaining the resource. While trading would give a windfall commercial gain to already privileged groundwater users, it could provide the inducement needed to establish a management regime that would lead to a more secure and resilient aquifer and increase the stream of future benefits. It is essential that groundwater allocations be capped for aquifers hydraulically connected to surface-water systems that are capped.

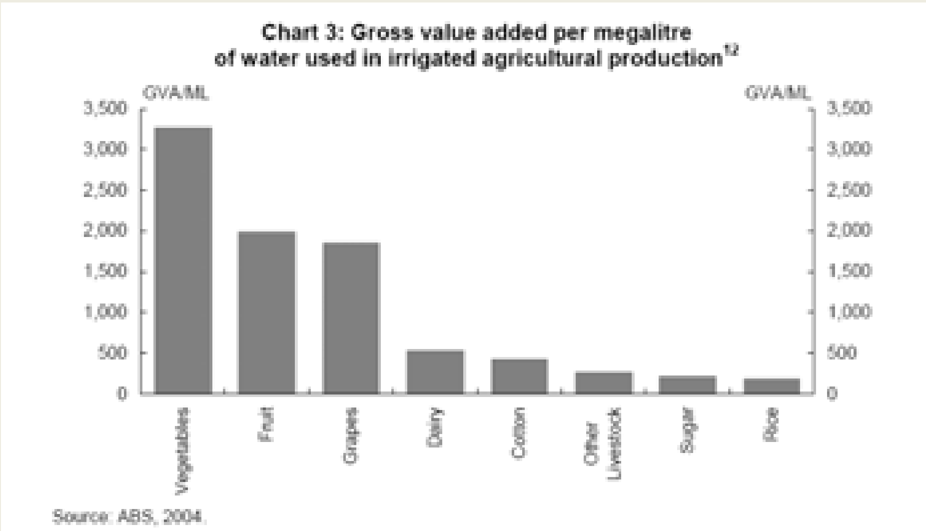
3.3 Managed aquifer recharge

Demand-side management has the disadvantage to groundwater users of constraining irrigated crop production to the level supported by groundwater resources, which appears in most groundwater irrigation areas to be a tighter constraint than land and labour. This creates an onus on groundwater managers to justify the need for restraint, against the likelihood of reduced farm income. This is a challenging task especially where users have a legal entitlement to extract more than can be supplied by the aquifer in the long term.

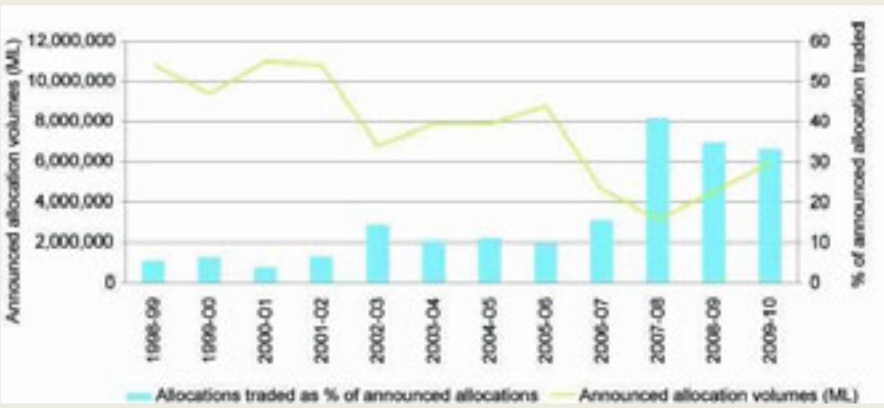
Box 7. Example of water-trading in the Murray-Darling Basin, Australia

In the Murray Darling Basin of Australia surface water trading takes place within a cap. The gross value added per megalitre (1,000 m^3) of water used for irrigation varies over an order of magnitude from rice (<A$200/ML), livestock, cotton and dairy up to grapes ($1,800/ML) and fruit crops and is maximized for horticulture ($3,200/ML). See figure from Roberts *et al.* (2006) below. This suggests there is significant potential to increase returns, or to secure returns for fixed-rooted crops, by trading between water users, and gross utility could be enlarged even with reduced water use. Note that this is gross value not net value at the farm gate, against which price of water would be compared by the irrigator considering selling or buying an allocation. At around this time, the price of temporary allocation trading of water in the Southern Murray Darling Basin varied from $80 to $700/ML, subject to the scarcity of the surface water resource (Kaczan *et al.*, 2011), and traded allocations totalled 20,000 ML/yr. It is important to ensure that a groundwater cap is in place to prevent substitution of groundwater for surface water. These systems should be assumed to be hydraulically connected, unless proven otherwise, and managed in an integrated manner.

In over-allocated groundwater systems, water allocation plans are expected to increase recognition of the state of scarcity and influence price on the water trading market. Noting the volatility of the surface water market, managed aquifer recharge could play a valuable role in conjunctive management of surface water and groundwater in systems that are capped.



Value of water uses from Roberts et al., 2006 (units A$, 2004)



Water allocation volumes and water sales as a percentage of water allocated in the southern Murray-Darling Basin from 1998/99 to 2009/10 (from National Water Commission, 2011a).

Box 8. Groundwater-trading in Australia – National Perspective

Groundwater trading in Australia in 2010–11
(adapted from National Water Commission, 2011b, p68-69)

Juris-diction	30/6/11 Entitlement	Traded Entitlement	Traded Allocation	Traded Entitlement	Traded Allocation	Number Entitlements	Number Traded	Number Traded	Total Number	Traded Number
	Volume (GL)	Volume (GL)	Volume (GL)	(%)	(%)		Entitlements	Allocations	Traded	(%)
Qld	1,038	0	2.3	0	0.2	15,264	0	35	35	0,2
NSW	1,934	74.9	31.2	3.9	1.6	74,179	151	155	306	0,4
Vic	863	27.8	4.2	3.2	0.5	10,706	265	70	335	3,1
SA	618	21.4	3.1	3.5	0.5	4,863	172	35	207	4,3
WA	1,772	22	8.1	1.2	0.5	10,562	78	12	90	0,9
NT	131	0	0	00	0.0	255	0	0	0	0,0
Tas	0	0	0			0	0	0	0	
ACT	1	0	0	0.0	0.0	144	3	0	3	2,1
Aust	6,357	146.1	48.9	2.3	0.8	115,973	669	307	976	0.8

Entitlements traded are permanent trades of an entitlement to use water. Allocations traded are the right to use water for the period (annual) in which the allocation is traded. The original groundwater-title holder can sell their allocation in subsequent years or retain it for their own use. The national volume of (annual) groundwater entitlements is similar to the annual surface water allocation from the southern Murray-Darling Basin. However, the proportion of groundwater entitlements and allocations traded is only 3% by volume in comparison with 15 to 55% for surface water systems. It is expected that trading will be less dynamic than for surface water systems where allocations are volatile due to strong dependence on recent rainfall, whereas groundwater typically responds to the accumulation of recharge and extraction over a number of years. In some areas, such as the Namoi Valley, New South Wales, groundwater and surface water allocation trading occur. As yet the synergies between managed aquifer recharge and water banking have not been explored, and it is considered unwise to do so until the surface water allocation is reduced to an environmentally sustainable level (Ward and Dillon, 2011).

An example of a Water Sharing Plan, and groundwater trading to restore the over-allocated Namoi groundwater system (adapted from NWC, 2011b, p 69-70)

The Namoi River region in north eastern New South Wales is an irrigated agricultural area where cotton is grown predominantly and also cereal crops, pasture and hay. Surface water is the preferred source but most farms also have access to groundwater, which is used more heavily in dry years. On average, groundwater use is 49% of total water use but in dry years it can reach 78%. Groundwater levels have been in decline for several decades and in 2006 a Water Sharing Plan was agreed covering 12 zones with differing degrees of water stress. Annual entitlements of 376 Mm3 surface water and 250 Mm^3 groundwater were issued. Seasonal surface water allocations are proportional to entitlements and are scaled on the harvestable flow in the river. Trading can occur in entitlements (permanent trade) and allocations (temporary trade).

Groundwater entitlements are being reduced to sustainable levels through the issue of non-tradeable supplementary licenses, which reduce to zero over a period of 3 to 10 years depending on the zone. The groundwater allocations traded reached 12 Mm^3 in each of 2005/6 and 2006/7 during a drought when annual groundwater consumption peaked at 206 Mm^3/yr. In subsequent wetter years, groundwater use declined to 136 Mm^3 and trading declined to 6 Mm^3 in 2010/11 while corresponding surface water use increased and surface water trading grew to 18 Mm3. It is evident that farmers are making use of trading of sustainable allocations to compensate for the decline in the volume of supplementary licences. That is, overall groundwater use is declining with water reallocated from lower-valued uses to higher-valued uses, based on trading mechanisms available to farmers under the Water Sharing Plan.

Hence, a 'two-handed' approach, demand- and supply-side management, can be very useful for groundwater managers.

In areas where there are seasonal excesses of surface water, supply-side measures such as managed aquifer recharge (MAR) can protect, prolong, sustain or augment groundwater supplies. As one of a suite of integrated water resources management strategies, this expands local water resources, reduces evaporation losses, and assists with replenishing depleted aquifers. In some circumstances where seasonal surface flows are large and aquifer replenishment is assisted by permeable soils, such as in the Burdekin Delta in Queensland, Australia, it is possible to avoid groundwater demand management altogether. However more usually, the amount of recharge that is economically or technically achievable is less than the annual groundwater deficit, and a combination of demand management and recharge enhancement is essential to restore a groundwater system to equilibrium (Dillon *et al.*, 2009b). In fact in confined aquifer systems, the act of recharge can directly enhance discharge.

There are many methods for recharging aquifers (e.g. Dillon *et al.*, 2009a), and these are selected based on the local hydrogeological characteristics, sources and quality of water available to be harvested. Importantly, cost per unit volume needs to be competitive with the foregone net benefits of demand reduction, taking into account the costs of managing demand and supply.

As an alternative to recharging the aquifer, groundwater supplies can be augmented or replaced by surface water supplies, such as canals and pipelines. This has the effect of reducing demand on the aquifer, but is perceived by groundwater users as a supply augmentation. In some places, this is misleadingly called 'virtual recharge', but that term is unhelpful when considering groundwater allocation systems (discussed earlier).

The complementary roles of demand management and expanding supplies, either via managed aquifer recharge or by providing alternative supplies are graphically depicted in Figure 4. Surprisingly, recharge enhancement is often left to groundwater users, and governments have tended to focus on demand reduction. A notable exception is the Indian Government through programmes such as under the Mahatma Gandhi Rural Employment Guarantee Act, which have supported a very large number of small scale water conservation projects, including managed aquifer recharge, but generally not yet within the construct of groundwater management plans that also constrain extraction.

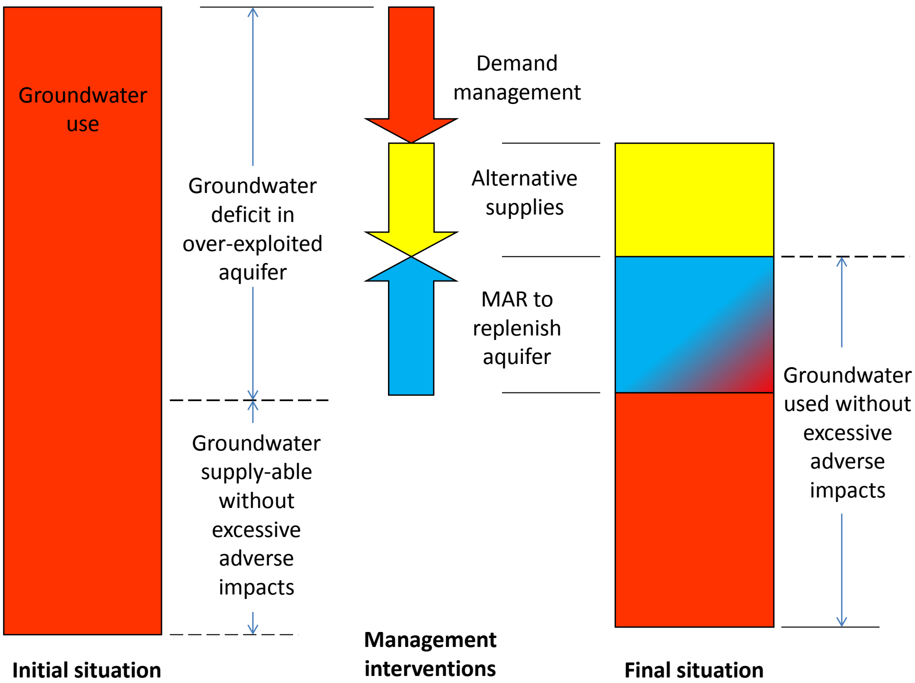


Figure 4. An aquifer can be brought into hydrologic equilibrium by either reducing extraction, or augmenting supplies, either through groundwater replenishment or providing alternative supplies.

Where surface water is in public ownership and groundwater in private ownership, the act of managed aquifer recharge effectively privatizes a public good, so MAR is best implemented where water entitlements are divorced from land ownership. The synergistic effect of managed aquifer recharge on implementing demand management has much potential but is yet to be exploited systematically.

Potential for managed aquifer recharge in relation to climate

In arid climates the lack of availability of a water source constrains the opportunities for aquifer replenishment. Runoff is so infrequent in arid areas that assets need to be cost efficient as they are actively utilized only infrequently, e.g. low level recharge dams in Oman (<100 mm rainfall) have been highly effective in detaining flash-floods to replenish alluvial aquifers (Fig 5(a)). Managed aquifer recharge is primarily for inter-year storage to increase long-term yield. However alternative supplies can also be considered. In the United Arab Emirates a new strategic groundwater reserve is being created in the desert near Liwa to replenish a previously depleted aquifer with desalinated water (flash distillation) that is a by-product of power generation when needs for power in Abu Dhabi exceed needs for the product water.

Van Steenbergen and Tuinhof (2009) and Van Steenbergen *et al.* (2011) have reported a wide range of watershed interventions that enhance groundwater recharge, retain soil moisture and reuse water, which they term the '3R concept' for climate change adaption, food security and environmental enhancement. These have been widely applied in arid and semi-arid areas of Africa, Asia and South America with startling results for improving the capability of land and farm income. They may be applied from land-holder scale up to sub-catchment and catchment scale and typically at very low cost and with active stakeholder participation and ownership by the community. The 3Rs encompass managed aquifer recharge and alternative supplies (reuse) in an integrated framework.

In semi-arid climates, water availability is a smaller constraint, and seasonal demand for water can be high, meaning that inter-season storage has high value in addition to inter-year storage. Inter-season storage can have immediate commercial benefits. At Cocoa Beach in Florida the aquifer is used to balance seasonal fluctuations in supply and demand for treated drinking water because the cost of an aquifer storage and recovery system is less than 2% of the cost of building more tanks. The well shown in Figure 5(b) can store and recover each year the volume equivalent to 10 times that of the adjacent tank.

(a) Recharge dam, Wadi al Fara, Oman

(b) ASR well, Cocoa Beach, Florida, USA

Figure 5. Some contrasting examples of MAR systems to replenish aquifers

In humid climates, opportunities for natural recharge are greater and the demand for storage is less, so managed aquifer recharge is expected to have a minor or niche role. Figure 6 gives a typology of climatic drivers and constraints for application of managed aquifer recharge. The horizontal axis ranges from arid at left to humid at right. The vertical axis represents seasonality of rainfall, ranging from highly skewed at the bottom to uniform throughout the year at the top. This diagram suggests that demand for water is highest at the left hand side, and demand for inter-seasonal storage is highest at the bottom. At locations where both attributes apply, the value of recharge enhancement is maximized, but opportunities for recharge enhancement with natural surface waters are improved where rainfall is higher. From this diagram Darwin is climatically the best suited of the Australian cities for managed aquifer recharge. Interestingly however, managed aquifer recharge has progressed fastest in Adelaide and Perth, because aquifers there are better suited for replenishment.

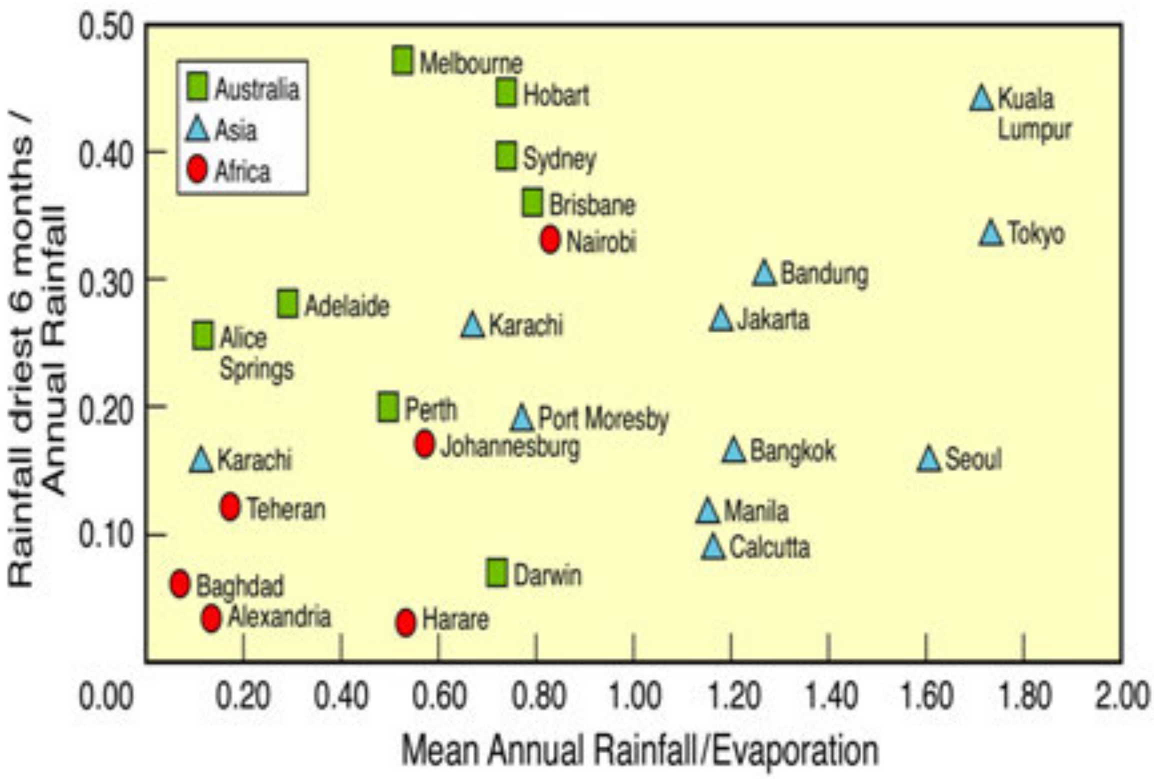


Figure 6. Climatic indicators of favourability for managed aquifer recharge as a water resources intervention strategy include measures of abundance and seasonality of rainfall.

Potential for managed aquifer recharge in relation to hydrogeology

The characteristics of an aquifer influence its capability for replenishment by managed aquifer recharge and the selection of recharge enhancement method. In general, depleted aquifers unconfined or confined, present the greatest opportunity. Hence managed aquifer recharge may be used as a remedial strategy, but only in conjunction with demand management. It is far better, however, to use managed aquifer recharge as a pro-active means of preventing depletion than as a restorative measure after problems have occurred.

The attributes of an aquifer impacting its replenishment potential are outlined in Appendix B (from Dillon and Jimenez, 2008). Unconfined aquifers are cheapest to recharge and also afford a greater variety of methods to be considered. A range of methods are also shown schematically in Appendix C (extended from Dillon, 2005). Consequently it is possible to map the opportunities for managed aquifer recharge based on hydrogeological characteristics. This has been done at national scale for South Africa by Murray and Harris (in South Africa Department of Water Affairs, 2010), as shown in Figure 7.

Such maps are only as good as the intensity and quality of data that are used to construct them. They should only be used as a screening method to ascertain the prospects more generally. To assess possibilities in a particular area more detailed local information will be necessary and if information is sparse, further hydrogeological exploration may be necessary before committing to recharge projects and strategies. In Australia, Geoscience Australia has adopted a localized screening model based on well yield (L/s) and salinity. Sites with high yields and low salinity are preferred. Where there are multiple aquifers, each is mapped and then a composite map of best prospects produced (e.g. Dudding *et al.*, 2006).

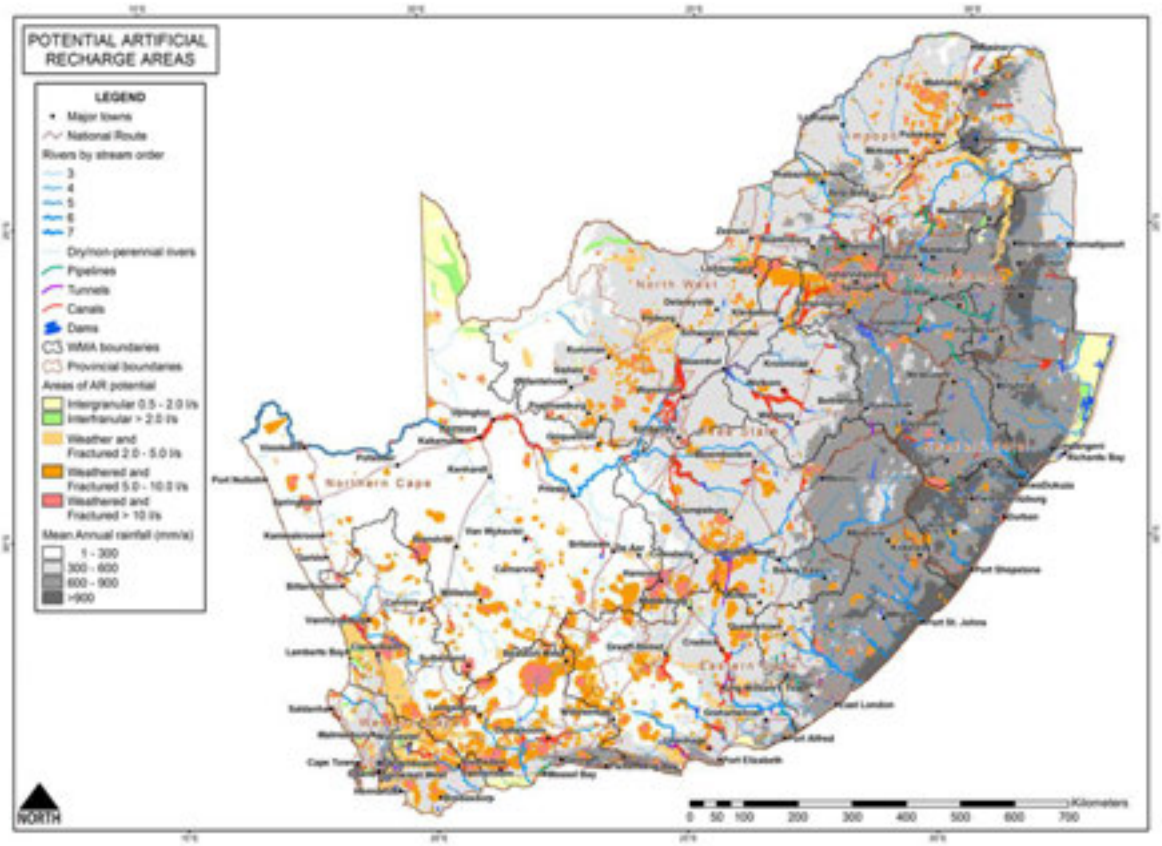


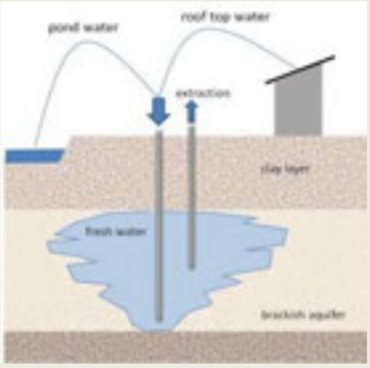
Figure 7. Map showing the potential for MAR based on hydrogeological conditions for South Africa (from South Africa Department of Water Affairs, 2010).

Box 9. Managed aquifer recharge in sand dams in Kenya

In the Kitui District, sand storage dams have been implemented on a large scale, and frequently in cascades. A sand storage dam consists of a relatively small dam, built on and into the riverbed of a seasonal river, behind which sand accumulates. The sandy layer acts as an aquifer, which is recharged with river water in the wet season and in which water is retained for use in the dry season. Sand dams are cost effective, they have on average a positive net present value, and for one sand dam (25 families) the net increase in family income is 25*125 = 3,000 US$/yr. The total investment cost vary from US$10,000-15,000, and annual maintenance and monitoring costs are estimated at 10% of the investment cost per year. Assuming two rainy seasons, the total storage capacity is about 4,000 m3/year (Tuinhof *et al.*, 2011). With this method a new aquifer, and subsequently new groundwater storage, is created. Moreover, the groundwater level in the area surrounding the sand dam may also increase, replenishing depleted groundwater. The storage provided by the sand dams is enough to provide water throughout the dry season for drinking water and to increase the area with irrigated crops. Sand dams may also provide down-stream benefits as they will reduce the river peak flow and may therefore mitigate downstream floods.

Figure, a. sand storage dam, b. fetching water in Kitui (*Acacia Water, 2007)*

Box 10. Fresh water injection in shallow brackish aquifers in Bangladesh



Bangladesh has abundant rainfall (>1,500 mm per annum in the coastal area), but this is concentrated in 3 to 4 months each year during the monsoon. Water shortages are acute during the last months of the dry season, especially in the coastal regions where freshwater availability is reduced by widespread brackish groundwater. In these areas, UNICEF, in collaboration with the Department of Public Health Engineering (DPHE) has initiated an action research project utilizing the abundance of water in the rainy season to augment freshwater storage in brackish shallow aquifers.

Four sites were tested in 2011, two with pond water infiltration (Batiaghata and Assasuni) and two with rainwater infiltration. The systems are constructed with locally available material and local manpower. Only a small pump is needed to lift the pond water to filter tank. From there the water is injected by gravity. The testing showed that approximately 700-800 m^3 of water can be infiltrated from the pond system while infiltration rates of sites with only rainwater were around 200-250 m^3.

The salinity data from the pond water infiltration sites clearly illustrate the positive impacts: at the end of the infiltration period the electrical conductivity (EC) in Batiaghata had lowered from 2,600 to 700 µS/cm and in Assasuni from 6,000 to 800 µS/cm.

The economic feasibility shows that the capitalized cost for construction and O&M are US$ 2-2.5 /m^3 which is cheaper than alternative solutions such as reverse osmosis and rainwater harvesting in tanks (both > US$ 8-10 /m^3) and water vendors (US$ 8-20 /m^3). Sixteen more sites will be constructed and tested in 2012, and the feasibility for up-scaling to 100-500 schemes in the following years will also be completed at the end of 2012.

Source: Albert Tuinhof, Acacia Institute

Box 11. Managed aquifer recharge in Mancha Occidental karstic aquifer, Spain, using wet year flows in Guadiana Channel to offset groundwater overexploitation.

The Spanish 23rd aquifer or UU.HH. 04.04, "Mancha Occidental" is, perhaps, the most emblematic example of over-exploitation of aquifers in Spain. The aquifer has an area of 5,500 km^2 and as a consequence of intense irrigation, the phreatic level has fallen by up to 80 meters and accumulated storage decline exceeds 100 Mm^3. The aquifer basin also maintains wetlands thanks to its overflow, at “Las Tablas de Daimiel National Park”, a Reserve of the Biosphere and a Ramsar system of wetlands.

The progressive deterioration of the aquifer and cumulative water table declines were also accompanied by an increase in groundwater salinity and deterioration of wetlands located down-gradient.

Confronted by water scarcity the aquifer was definitively declared as “overexploited” and the Confederación Hidrográfica del Guadiana adopted measures to restore the water imbalance. They built a battery of infiltration wells along the head area of the aquifer in order to store surpluses of water in the wet hydrological years. Therefore, it is an “occasional availability” scheme included in the governance arrangements for flow and management, notably in floods. Twenty-five wells up to 90 m deep, were drilled in some highly-transmissive areas of the karstic aquifer, in three successive campaigns (1997, 2000 and 2010). Wells were distributed over about 30 km along the “Canal del Guadiana”, downstream of Peñarroya dam. The good quality of recharge water that is pretreated using filtration and settlement has permitted relatively simple, “low-cost”, recharge operations, although some problems occurred with air clogging (Fernandez, 2010a).

The last cycle of recharge, between January 2010 and March 2011, took advantage of a wet hydrological year, and recharge in this period exceeded 50 Mm^3. The aquifer is still heavily exploited, although impacts are being mitigated through changes in water management practices and improvements in governance schemes. It is a modern challenge to be applied in an area where competition for water has been a traditional source of conflict.

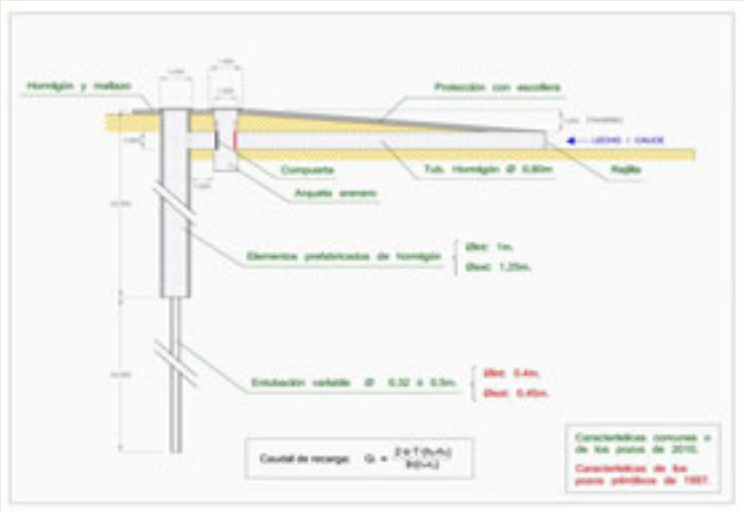


Diagram of a recharge well and photograph of recharge well gallery under construction near Canal del Guadiana.

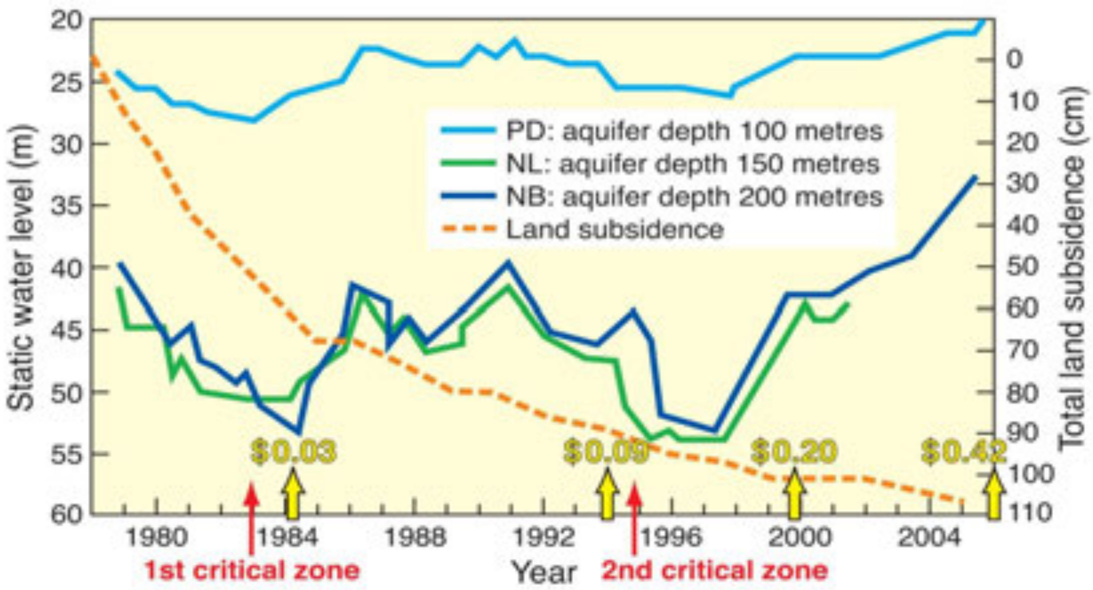
RAMSAR wetlands supported by the Mancha Occidental aquifer	Managed aquifer recharge in Tablas de Daimiel National park

3.4 Alternative supplies

Where it is more economic or pragmatic to provide an alternative distribution system to groundwater users than to replenish the aquifer and use existing water supply wells, the most logical solution or combination of solutions should be adopted. Examples of successful recovery of overexploited aquifers include extending provision of surface water supplies to Bangkok (see Box 12) and piping effluent from Mexico City to Mesquital Valley irrigation area. However it is necessary to ensure that these supplies substitute for groundwater use, rather than just augment it in order to regain groundwater equilibrium.

Box 12. Reversing chronic subsidence in Bangkok by providing substitute supplies and using ground water pricing to modify demand.

In Bangkok, groundwater extraction for public water supplies, as well as for industrial, aquaculture and agricultural uses, led to groundwater levels in decline, increasing groundwater salinity, deepening spread of pollution, land subsidence and consequent flooding. For many years, this was regarded as a chronic intractable problem, as there were so many difficulties for groundwater managers in locating wells, estimating abstraction, implementing a control system and obtaining compliance with the rule of law while the city continued to grow. However, the government found a solution through provision of alternative surface water supplies, in key areas of over-abstraction and imposing charges on groundwater use so that surface supplies were cheaper. Groundwater levels recovered and now water pricing policy is used to adjust the balance of groundwater and surface water use so as to keep groundwater levels within their desired range, while covering the costs of water supply and water resources management (Buapeng, 2009).



Groundwater level decline and recovery in three aquifer depths at Ramkamhaeng University in central Bangkok showing the stabilization and recovery of groundwater levels as a result of groundwater pricing policies that made surface water supplies more attractive. Note that land subsidence rate has declined and stabilized as a result of groundwater level recovery. The times at which prices changed and the price in US$/m^3 are shown (adapted from Buapeng, 2009).

3.5 Non-renewable resources with lack of alternative supplies

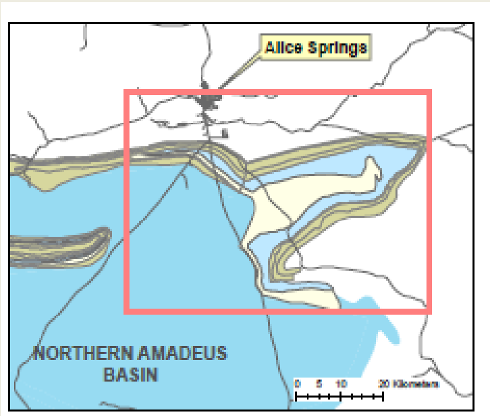
In exploiting non-renewable groundwater resources, the consequences of progressive decline in storage need consideration and plans developed and communicated to address depletion. The costs of accessing the next nearest resource need to be compared with the social and economic benefits of the continued existence in that place of the town or industry. Invariably, minimizing consumptive demand has the effect of prolonging the supply and of deferring and minimizing the cost of accessing remote resources. Box 13 describes a situation where a thriving town is located on a depleting groundwater resource, and the nearest viable alternative water resources are very remote.

Box 13. Mereenie sandstone fossil groundwater management plan

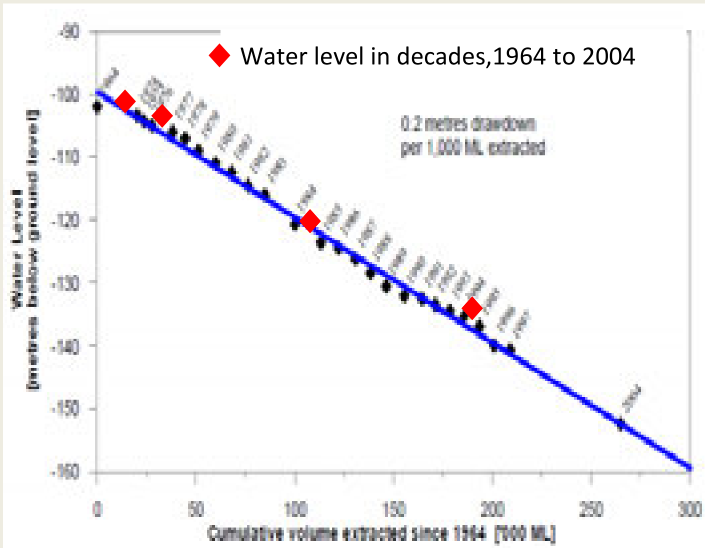
The public water supply for the town of Alice Springs (population 27,000) in arid Central Australia (280 mm/yr rainfall and 3000 mm/yr potential evaporation) is supplied almost entirely from the Mereenie Sandstone aquifer system of the Amadeus Basin. Groundwater in this aquifer is considered "non-renewable" because the rate of recharge is insignificant compared to the volumes extracted for public water supply.

The Roe Creek Borefield is located about 15 km south of Alice Springs and comprises about 28 production wells drilled to a depth of about 570 m in the Mereenie Sandstone. The fresh groundwater has been dated as between 10,000 and 32,000 years old, indicating a fossil resource recharged during much wetter periods in the past (Barnett et al., 2010).

Since pumping began in 1964, about 254 Mm^3 have been extracted with a rate of 8 Mm^3/year since 1991. As a result, groundwater levels in the Roe Creek area have fallen at a rate of 0.2 m per Mm^3 extracted, from an original depth of 100m to about 150m below ground. The more or less linear rate of drawdown led to the description of a "tank model" (Jolly *et al.,* 1994), whereby water is extracted from the aquifer as if from a tank, with virtually no additional inputs from surface recharge or lateral flow.



Location of Mereenie Sandstone aquifer



Drawdown versus extraction (Jolly et al., 1994)

The potable water supply aquifer is effectively being slowly mined, and this information was made available to the public in fact sheets and published reports. However, water use was 580 litres per person per day, more than double the average water consumption in Australian cities. A public consultation process began that resulted in the Alice Springs Water Resources Strategy 2005 (Northern Territory Government, 2007).

This established a fundamental principle for the use and management of this non-renewable source – "not more than 80% of the estimated aquifer storage can be depleted over a period of 320 years (i.e. 25% of the maximum allowable drawdown is permitted every 100 years)." Estimates of potable aquifer storage and projected water-supply demand indicate at least 100 years, and perhaps up to 400 years, before the aquifer is depleted. Demand management is central, with capping of town water supply abstraction and water-use efficiency plans adopted (Turner *et al.*, 2003). Additionally, water from the wastewater treatment plant is further treated through a water-recycling plant and recharged via soil aquifer treatment basins, to overcome sewage overflows to a natural wetland in winter, and as a by-product replenishes the aquifer remote from the well field, reducing the net rate of depletion. When augmentation is ultimately necessary, groundwater at Ti Tree Basin, 150km north could potentially be tapped.

3.6 Economics of groundwater use and demand management

Firstly considering the costs and benefits of groundwater supply to a groundwater user, for example in irrigation, the costs are composed of the capital cost of the well amortized to annual volume and energy costs for pumping. The value of their water use is proportional to use when use is highly efficient, but with excessive irrigation there are diminishing marginal benefits (Fig 8). However, the full cost of supply includes environmental costs not borne directly or immediately by the groundwater user, such as flow depletion in streams, ecosystem impacts, salinity increase, loss of income by other groundwater users who lose access to groundwater and higher pumping costs for other groundwater users, in addition to consideration of shortened useful life of the aquifer due to depletion. Hence, while an individual groundwater user perceives no constraint on profligate use of water, there is a volume beyond which there is a decline in the utility of the aquifer for the community at large.

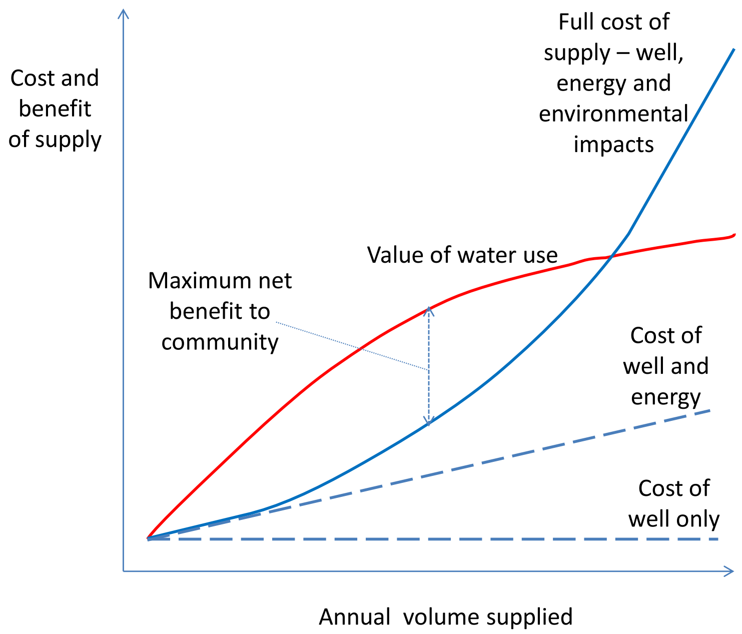


Figure 8. Costs and benefits of groundwater use in relation to volume of use as experienced by a single groundwater user and by their community and environment at large.

One corollary of this concept is a dry economic argument to suggest pricing of groundwater to constrain consumption. It is important to note that this is only one of a range of possible management interventions; and its effect on groundwater use is illustrated in Figure 9. A price per unit volume is charged to the groundwater user to encourage efficiency of use and so that the utility function of the groundwater user is optimized at the same annual volumetric use that optimizes the net benefits to the whole community. Just as there are environmental externalities associated with groundwater storage depletion, there are social and economic benefits of irrigation production that exceed the revenue stream to the groundwater user. These factors would need to be taken into account if implementing such a pricing system and account for the way in which revenue was used.

3.7 Economics of incorporating managed aquifer recharge and alternative supplies

Managed aquifer recharge (MAR) can increase the value of water resources by transferring surface water in times of abundance to add to groundwater storage and thereby conserve water. This replenishes depleted groundwater and avoids evaporative losses, salinity increase and possibilities for blue-green algal blooms if the water had been retained in surface reservoirs. The surface waters used for managed aquifer recharge may include natural waters from catchments, urban stormwater, water recycled from treated sewage effluent,

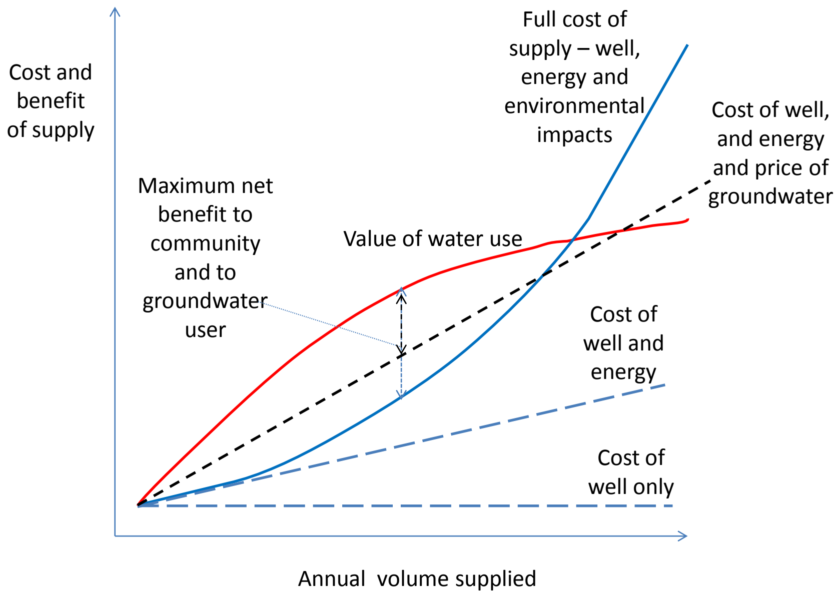


Figure 9. Costs and benefits of groundwater use in relation to volume of use as experienced by a single groundwater user, including a price of water so that user and community utility are maximized by their community and environment at large.

desalinated water from brackish aquifers or the sea, and suitably treated industrial effluents. There is ample guidance on protecting human health and the environment for managing aquifer recharge operations (e.g. NRMMC, EPHC and NHMRC, 2009, and Page *et al.*, 2010). However, guidance on policies to account for MAR in water resources management is embryonic (e.g. Ward and Dillon, 2011) and institutional arrangements are rare (a notable exception being the Arizona Water Bank). In semi-arid areas, recharge is generally in the monsoon or wet season, and recovery occurs in the dry season (Figure 10.) Aquifers that are already depleted make excellent storage targets because there can also be environmental benefits in replenishing such aquifers. However, care is needed to ensure that groundwater replenishment is not at the expense of surface water ecosystems and water users downstream. Ideally, there is an integrated surface water and groundwater allocation plan, accounting for their connectedness.

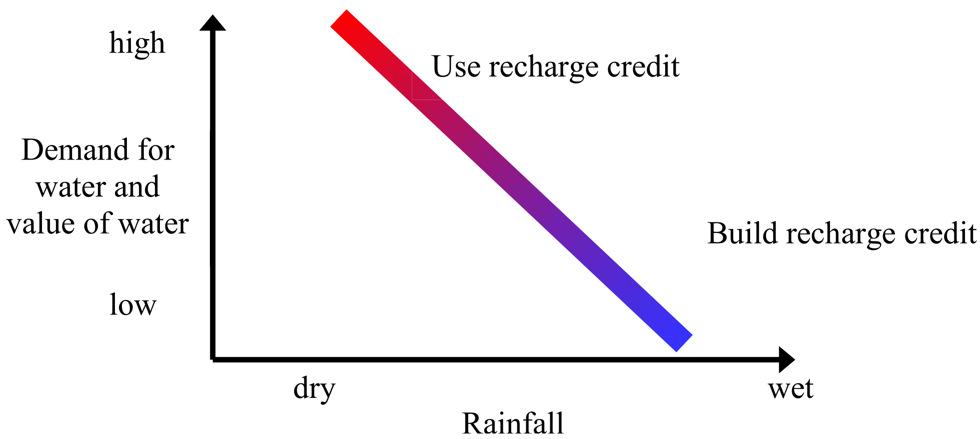


Figure 10. Managed aquifer recharge is a way of increasing the value of water resources by harvesting and storing water in the wet season for recovery during the dry season or as drought and emergency supplies.

A theoretical construct for prolonging the time to yield failure and for restoring currently over-exploited aquifers using a combination of demand management and recharge enhancement was presented by Dillon *et al.* (2009b); see Appendix A. The full paper included case studies in Australia and India. However, it did not address a determination of the most economic proportion of recharge enhancement and discharge reduction necessary to restore a depleting aquifer. That concept is introduced here.

For any aquifer, there will be a range of recharge options that can be ranked in order of increasing unit cost of supply. Similarly, foregoing extraction for each use of groundwater will have a range of unit costs that can be ranked in increasing order. Each element of these lists has an associated volume and unit cost and the two lists may then be merged to identify the cheapest option and the volume of demand reduction or supply enhancement expected if that option were implemented (Figure 11). Depending on the degree of over-exploitation, a series of options may be required to achieve hydrologic equilibrium (as per Figure 4), or at least to extend the effective lifetime of the groundwater resource.

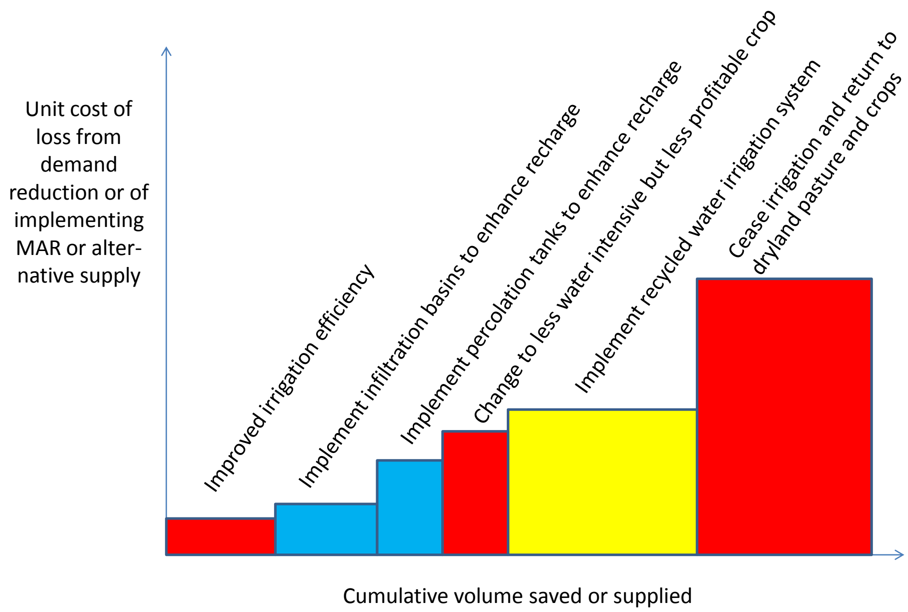


Figure 11. A logical combination of demand reduction (red), recharge enhancement (blue) and substitution of alternative supplies (yellow) may be made to reduce or eliminate groundwater depletion at least cost. Options and their relative costs and volumes are location-specific. However, improved irrigation efficiency is often the least costly option and hence implemented first.

Figure 11 reveals plainly to groundwater users the choices to be made by stakeholders and the benefits of investing in recharge systems or alternative supplies, in relation to the investments in improving irrigation efficiency or the costs borne by changing crops or retiring irrigated fields to dryland systems. The decisions will depend on the relative costs of options and the capability of stakeholders to absorb costs. One way of covering costs for recharge systems could be to impose a unit volumetric charge for groundwater (as per Figure 9) which would also have the effect of encouraging irrigation efficiency. Implementing a charging system for groundwater is unlikely to elicit an enthusiastic response by groundwater users. However if they can see that their contribution to recharge facilities would be at a lower cost to them than the revenue otherwise foregone by reducing consumption by an equivalent volume, such a system would be easier to implement. This is how groundwater replenishment was able to commence in the Orange County Water Management District in California. The imposition, with community consultation, of a “groundwater replenishment assessment” funded the operations that reversed the salinization of the over-exploited coastal aquifer. This has subsequently paved the way for larger replenishment systems using better quality water to improve the security, yield and quality of groundwater supplies (Mills, 2002).

Box 14. Three-pronged approach to managing groundwater storage in Arizona, USA

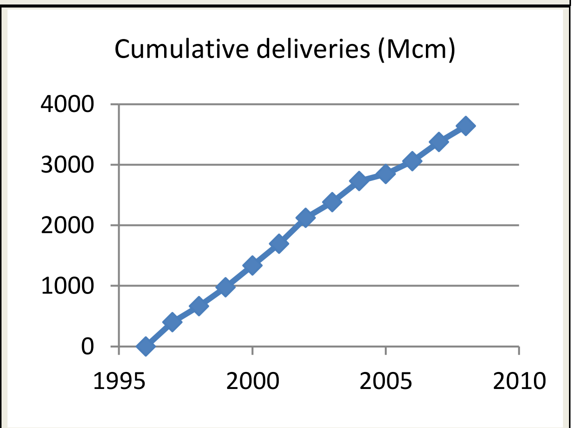
Arizona, a State with declining groundwater levels, rapid urban population growth and vulnerability to drying water supply catchments, adopted its Groundwater Management Act in 1980 to curb groundwater overdraft (Megdal, 2007). The act was amended in 1986 to encourage recharge of groundwater with surface water in times of excess flows and recycled water derived from treated sewage effluent (Megdal, 2007). Subsequently, the Central Arizona Project (CAP) was completed, with a capacity to divert 1850 million m^3/yr (20% of Arizona water use) from the Colorado River lifting it up to 730m and delivering via a 540km canal. This provides a substitute supply for irrigation and municipal use in three groundwater Active Management Areas (Phoenix, Pinal and Tucson AMAs). It is also a dominant source for groundwater recharge, under the 1986 laws that allow banking of water to meet future needs, and for drought relief (Megdal, 2007). Recharge and recovery also serves as a mechanism for cities to use renewable Colorado River water indirectly rather than through construction of costly treatment plants (Megdal, 2007).

Arizona's innovation in groundwater recharge and the scale of its practice are possible due to extensive unconfined aquifers of high transmissivity, containing good quality drinking-water supplies and overlain by permeable soils, as well as a highly developed system of permitting and reporting. These ensure that recharge is cost-effective, and the benefits of water storage or banking are broadly dispersed and highly valued. A key component of Arizona's approach to water banking was the establishment in 1996 of the Arizona Water Banking Authority (AWBA). The AWBA was created to store water for multiple purposes; (1) storage for drought relief for CAP users; (2) support groundwater management goals of AMAs; (3) support settlement of Indian water claims; and (4) bank Colorado River water separately to assist Nevada and California (Megdal, 2007). AWBA invests funds derived from land taxes associated with the CAP, a levy on groundwater extraction in the Active Management Areas, and initially also from State appropriation. Investment in water banking by municipalities and urban developers in order to meet supplies for 100 years for new developments also contributes to recharge, but is not coordinated by AWBA.

In the 14 years from inception to end of 2010, the AWBA had expended US$ 272M to accrue 4,300 Mm^3 of recharge credits at an average cost of 6.3 cents/m^3. Of this volume, 84% was for intrastate credits and 16% was banked on behalf of Nevada (from Arizona Water Banking Authority, 2011).

Hence in Arizona, law that quantifies groundwater rights, water banking to increase groundwater storage and the CAP project substituting surface water for groundwater use are the combined governance elements to reverse storage depletion. Further, in 2007, the Secretary of Interior signed a shortage sharing regulation and there is also work towards developing an agreed-upon groundwater recovery plan. Arizona's supply- and demand-side regulations provide more degrees of freedom to address potential future reductions in surface water flows and ability to recharge than demand-side management alone. Continued scenario planning is expected to give even more resilience in addressing water scarcity.

Agua Fria Recharge Project infiltration basins recharge CAP water to replenish groundwater and accumulate a recharge credit for future groundwater use (from Arizona Water Banking Authority).



Cumulative water deliveries by Arizona Water Banking Authority 1997-2008 (Arizona Water Banking Authority 2011).

3.8 Further groundwater management questions and principles

Why manage groundwater recharge/discharge or storage and which?

For many years, dates and coconuts were high-valued products of groundwater irrigation on the coastal Batinah Plain of Oman. The subsequent establishment of irrigated lucerne for goat fodder on the sandy plains inland was a very much larger use of water for a much lower-valued product that could even be imported at lower cost. However, due to the lucerne production, saline groundwater ingress occurred causing large areas of palm groves to die and the rest threatened. An industry was lost and land salinized because of inadequate understanding and management of groundwater. This is an example of where the value of effective management of groundwater could have amounted to the total ongoing value of production based on groundwater supplies.

Investment in groundwater management is a fundamental responsibility of government and one with high benefit-to-cost ratio, with significant social value particularly where aquifers are stressed and competition among users is high.

Who sets the objectives? Stakeholders or governments?

While governments have the responsibility for management, setting the objectives and forming plans involves engagement with stakeholders to achieve success. Several models for engagement are in common use. **Catchment or aquifer management boards** may be empowered to make decisions or to make recommendations to a Minister of Water Resources who makes the final decision. Such boards commonly consist of stakeholder community representatives with some technical support from government departments.

In some cases boards may be empowered to generate their own resources, for example by imposing a water resources management levy on groundwater users, land owners, or local government bodies within the catchment or groundwater system. These funds support monitoring, reporting, informing stakeholders, developing water management plans and implementing them.

Other bodies such as **groundwater users associations** may be formed to support the interests of their members. These may suggest or even fund initiatives for recharge enhancement, alternative supplies or communally-supported improvements in irrigation efficiency. In Spain, water managers have developed a range of methods to establish participatory schemes for groundwater and environmental stewardship by water users.

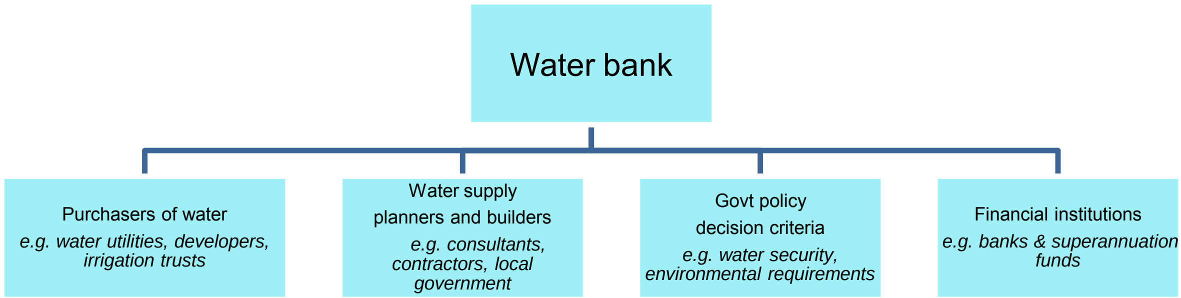


Figure 12. A water bank can provide a transparent approach to water resources development and allocation decision-making.

This unifies the demand and supply market for water over a region that is larger than that considered by single purchasers and suppliers and thereby can create efficiencies in costs, water utilization and maximize resource utility while meeting social and environmental needs.

Institutions such as **water banks** (Fig 12) can also be established by governments to establish the mix of water resources in use where demand is growing. These can identify the specific options for new supplies or water conservation (as in Fig 11) and the means of funding these to minimize costs of achieving government policy objectives in regards to water, agriculture, environment, and urban and land planning and development. An example is the Arizona Water Bank (Box 14) that makes investments in managed aquifer recharge to meet needs for a growing population in an arid area with an extensive and transmissive aquifer. This is a very lean operation staffed by only two to four people. That model may be extended to address all sources and uses of water in a region, and has potential to be a key institutional initiative for adaptation to climate change.

Changing climate, population and land use and changing recharge and discharge expectations and process for revision of objectives

No water allocation plan is expected to endure indefinitely. Changes in magnitude and spatial and seasonal patterns of demand, variations in expected recharge rate and changing social considerations of the trade-off between level of economic production and environmental consequences need to be accommodated. Improved knowledge over time of the status of groundwater and surface water resources and their dependent ecosystems will also affect the level of allocation, which would be adjusted periodically (as per Fig 3). In semi-arid systems of southern Australia with slowly changing groundwater storages, allocations are typically required by law to be re-evaluated each five years with public consultation on allocation plans prior to adoption and implementation. This periodic revision of allocation plans also allows consideration of supply-side measures such as managed aquifer recharge and alternative supplies.

Managing falling and rising trends

Generally, the value of groundwater use depends on the volume and timing of that use. The environmental impacts generally relate to change in the level of the water table where this was initially in close proximity to the ground surface or beneath stream channels, lakes or the sea. The costs and greenhouse-gas emissions of groundwater extraction depend on groundwater levels in the vicinity of pumping wells. This is also the area most prone to land subsidence where porous media are compressible. Hence the benefits of consumption relate to volumes and the costs relate to levels.

Where unconfined aquifers have a deep water table prior to development or are distant from receiving streams, the immediate environmental costs are likely to be least. Aquifers with high effective porosity are more likely to yield more benefit per unit of environmental cost. However aquifers that contain *qanats* (groundwater *aflaj*), or intermittently hydraulically connected ephemeral streams or only shallowly incised receiving streams are highly vulnerable to small changes in groundwater levels adjacent these features. In these circumstances, the proximity of groundwater extraction is as important as the volume. These discharge zones need to be considered carefully when allocating groundwater entitlements, and exclusion zones may be specified (e.g. in UAE near *aflaj*). Surface water bodies are also potential sources of water for groundwater replenishment, subject to surface water allocation plans; however the counter-cyclic timing of recharge and demand and the importance of flow in dry periods require quite sophisticated management approaches. A simpler option, where available, is to replace groundwater allocations with alternative supplies in these more sensitive areas.

Groundwater management is also needed where groundwater levels are rising due to change in land use (such as large-scale removal of deep-rooted vegetation), climate change or importing water supplies that result in drainage of excess water to a water table. This can result in restricting land use change, developing conjunctive use of groundwater and surface water to offset rising levels, and introducing pricing systems to encourage balance of use from sources that allows hydraulic equilibrium to be established in the aquifer in an acceptable depth range. As a last resort, groundwater drains may be used, taking account of the impacts on surface-water systems down-gradient.

Transitional arrangements for sustaining resources

For groundwater managers facing legacy deficits and an inadequate legislative framework, transitional strategies are needed. Many jurisdictions are a long way from an aquifer-friendly entitlement system, either for groundwater use or for managed aquifer recharge credits. However most have permit-based systems in place to allow use or recharge. Further information may be needed to enable consumptive pool-entitlements to be well defined and to define sharing arrangements. A transitional pathway is needed to progress towards intended governance arrangements that optimize the value of the water resource (Fig 13).

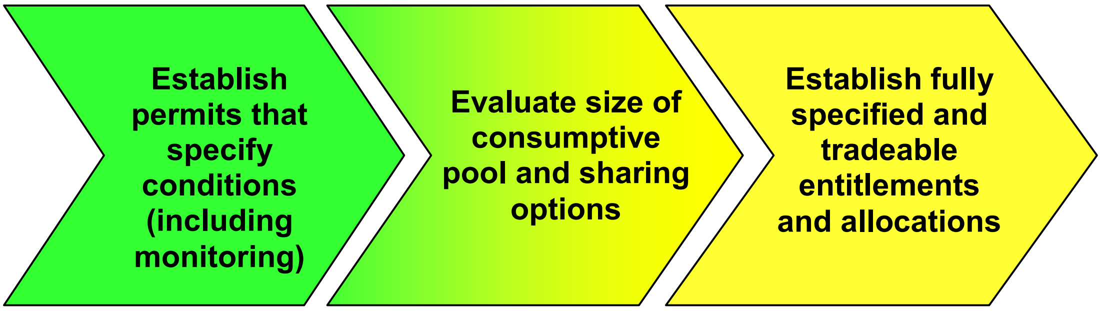


Figure 13. Pathway for policy implementation from regulation to entitlements

Metrics for monitoring and management

Monitoring the progress towards the intended objectives of groundwater management provides the only defensible assessment of the effectiveness of management. Clear criteria are needed that relate to economic productivity, environmental and social factors. Productivity in irrigation areas is usually recorded by departments of agriculture who survey farmers, and evaluate yields and prices. Water use is a useful measure where resources allow as this gives clear feedback to irrigators on their water use efficiency. It would normally be expected for all public water supplies to record volume extracted, as well as monitor its quality. Groundwater levels in environmentally sensitive areas, and in the drawdown cone of centres where wells are dense, are valuable. More sophisticated measures include the area where piezometric surface is above sea level (or some other defined level) at the end of the irrigation season, or estimated recoverable storage volume based on a network of piezometers. Social indicators may include the number of groundwater users who have improved irrigation methods, the number of investors in managed aquifer recharge projects, time required for irrigation management. More comprehensive lists are given by Beernaerts (2006).

Integrated water resources management of quantity and quality

For historical reasons, the management of water allocations has largely been undertaken by natural resources management (NRM) authorities, and the management of water quality by environmental protection and health authorities (Figure 14). Because quantity and quality are interdependent this often leads to harmony between authorities on policies, but on some occasions can lead to conflicting objectives. Managed aquifer recharge with water of slightly poorer quality than the native groundwater, but of much better quality than groundwater degraded by saline intrusion, is an example, where the NRM department is in favour but the environment protection authority is not. A holistic view is required with an understanding of the consequences of the alternative management scenarios for both quantity and quality in order to find a path that optimizes the utility of the aquifer, while meeting public health and environmental constraints. An aquifer that provides unrestricted irrigation but no drinking water supply may be a sub-optimal strategy when costs of alternative supplies are taken into account.

National government role in setting water resources management policies and principles

In many countries, there is a hierarchy of government policies at national, State, catchment and local level, with national government taking responsibility for establishing governance principles, investing in water management initiatives and ensuring coordination of policies across state jurisdictions which generally have statutory responsibility for water management. Within catchments and groundwater systems, these policies are enacted including monitoring and evaluation of the resource, with devolved state technical support for informing and consulting with stakeholders and in establishing and maintaining accounting systems for entitlements and allocations. At local or village level, action in implementing on-ground practices and infrastructure enacts change in accordance with policies set at higher levels, combined with local innovation and adaptation.

Many examples of highly effective local interventions to restore groundwater storage and resilience, reported earlier, have been initiated at local level. They have not relied on supportive national water-resources policies, although the presence of such policies would greatly expand such initiatives. However, rural employment and agricultural extension services at national and State levels have facilitated change. For example, the Mahatma

Attribute Instrument Examples	Quantity NRM policies Ward and Dillon 2009	Quality Water quality management guidelines NRMMC-EPHC-NHMRC 2009a
Management Issue Resource	Water and Storage Entitlements and Allocation	Human Health and Environment Protection
Surface water	• Environmental flow requirements (including urban stormwater and sewage effluent) • Water allocation plans and surface water entitlements • Inter-jurisdictional agreements	• Catchment pollution control plan • Water quality requirements for intended uses of recovered water • Risk management plan for water quality assurance
Groundwater	• Resource assessment accounting for groundwater-dependent ecosystems • Groundwater allocation plan and groundwater entitlements • Demand management • Allocatable capacity and entitlement for additional storage in the aquifer • Transfer of entitlements among groundwater users and from MAR operations • Inter-jurisdictional agreements	• Groundwater quality protection plan • Account for recharged aquifer in accordance with MAR guidelines • Water quality requirements for intended uses of groundwater • Risk management plan for water quality assurance beyond attenuation zone, accounting for aquifer biogeochemical processes

Figure 14. Integrated natural resource management and health and environment issues to be addressed for effective governance of surface water and groundwater resources involving managed aquifer recharge (adapted from Dillon et al., 2009a)

Ghandi National Rural Employment Guarantee Act (2005) has invested more than 50% of up to US$ B8/year on water conservation, harvesting and groundwater replenishment works.

In the inaugural Indian Water Week, in April 2012, the Government of India (2012a) released for public comment a Draft National Water Policy. Revised in June 2012, this presents a comprehensive approach to integrated water management of surface and groundwater (quantity and quality) with objectives of equity, social justice and sustainability (Box 15). It declares that, whereas groundwater is currently "*still perceived as an individual property and exploited inequitably and unsustainably in places*", that water needs to be "*managed as a community resource, held by the state under public trust doctrine to achieve food security, livelihood, and equitable and sustainable development for all*." If this draft policy is implemented and used to help frame activities supported by NREGA and other government programmes, it would have the largest international impact on reducing the groundwater imbalance quantified earlier.

Box 15. Contents of Indian Draft National Water Policy

Govt. of India
Ministry of Water Resources
DRAFT NATIONAL WATER POLICY (2012)

1. Preamble
2. Water framework law
3. Uses of water
4. Adaption to climate change
5. Enhancing water available for use
6. Demand management and water use efficiency
7. Water pricing
8. Conservation of river corridors, water bodies and infrastructure
9. Project planning and implementation
10. Management of flood & drought
11. Water supply and sanitation
12. Institutional arrangements
13. Trans-boundary rivers
14. Database & information system
15. Research & training needs

4. Prospects for slowing or reversing trends through improved governance

4.1 Conclusions from case studies

The case studies presented in boxes in the previous section reveal there is considerable scope for securing social, economic and environmental benefits through selection and adoption of governance methods relevant to the situation and to the affected community. Table 2 summarizes the key questions concerning the state of the aquifer before the intervention, the capability of the community for collective action (which in most cases was revealed as part of the process of engaging with the community) and whether alternative water supplies were available. These answers determined the suitability of the three categories of groundwater governance, which are colour coded in Table 2 to match Figures 4 and 11.

Table 2. Concise summary of case study attributes, management instruments employed and effectiveness

Case study	Was g/w over-allocated?	Existing social capability for collective action?	Sufficient other water resources available ?	Demand management	Managed aquifer recharge	Alter-native supplies	Effective-ness#
Llocos Norte, Philippines	No	Yes	Localized	Farmer led			Yes
Andhra Pradesh, India	Yes	Yes now	Ephemeral streams	Farmer led	Localized		Yes
Maharashtra, India	Yes	Yes	Ephemeral streams	Ban on tube wells and sugar cane	Strategic		Yes
Castilla y Leon, Spain	Yes	No	River and treated wastewater	User collective failed to curb use	Basins	treated waste-water	No
Namoi Valley, Australia	Yes	Yes	Namoi River	Entitlements issued		river water (also licensed)	Yes
Kitui, Kenya	Yes or not available	Yes	Ephemeral streams		Sand dams		Yes
Coastal Bangladesh	Water too brackish	Yes	Rainwater and pondwater		Recharge wells		Yet to be assessed
Mancha Occidental, Spain	Yes, heads fallen 80m	Unknown	Canal del Guadiana		Recharge wells	Guadiana channel	Yet to be assessed
Bangkok, Thailand	Yes- heads fallen 60 m, land subsidence	Not relied on. Diverse and dispersed g/w users	Treated surface water	Pricing to curb demand		treated surface water	Yes
Alice Springs, Australia	Yes – heads fallen 50m	Governmen t is dominant user	Treated wastewater	Entitlements and use efficiency measures	Minor soil aquifer treatment		Yes for adopted objective
Arizona, USA	Yes	Yes	CAP and treated wastewater	Groundwater rights assigned	Water banking	CAP and treated waste-water	Yes

Storage objectives (and water quality objectives where known) are met, and management process is accepted by groundwater users.
Blank cells indicate that the particular governance instrument was not applied in that situation.

The right-hand column of Table 2 is an interpretation of the effectiveness of the governance arrangements, based on the reporting of these interventions. That is, if groundwater storage increased where it had previously been depleted, management was considered effective. In one case, in coastal Bangladesh, the replenishment was intended to establish fresh groundwater in a previously unusable brackish aquifer. Although results are too early to judge success at this site, that method has been used effectively in Australia for the same purpose (e.g. Dillon *et al.*, 2009a).

Single strategy interventions were used in only three of these cases and each of them was for groundwater systems that either were initially in hydrologic equilibrium (Llocos Norte, Philippines), or water was brackish (Bangladesh) or where there was a low rate of use or no use because the scale of the resource was small (Kitui, Kenya). In each case there was a high degree of cooperation inherent in the community so there was confidence that new resources would be managed for the equitable benefit of the community.

In five cases, there was one demand-side measure and one supply-side measure used together. In Maharashtra, Andhra Pradesh, and Alice Springs cases managed aquifer recharge is being used selectively for groundwater replenishment, and in Bangkok and Namoi Valley alternative surface water supplies are used to replace groundwater use and restore groundwater equilibrium.

In two cases, supply side management alone is applied and in the older of these two cases, groundwater levels are continuing to fall because the increase in supply has been met by a corresponding increase in demand.

The final case, in Arizona, contains the three management interventions used concurrently and is providing a robust means of managing groundwater resources in an area with significant population growth and a dry and drying climate.

In all successful cases, consultation with the community was important, so stakeholders could understand the nature of the problem, the options for dealing with it and contribute selecting and shaping the options in line with resources available. The table shows that unless the community is small and cohesive, concentrating on effective demand management is essential and should precede supply-side options. Supply-side options may be used as inducement to participate in demand management, recognizing that in some circumstances it may be more economic to cover supply costs in order to maintain production than to rationalize production, as illustrated in Figure 11.

A current limitation for managed aquifer recharge as a groundwater management strategy is the lack of experience of most water resources agencies with its use. Siting, design, operation, maintenance and water-quality protection are topics that need to be understood, so that investment in managed aquifer recharge projects provides consistent ongoing success. There is an uneven spread of knowledge and competence in implementation and maintenance of projects, particularly in developing countries, where it can be highly competitive for enhancing, sustaining and improving water quality of town and city drinking-water supplies, as well as agricultural supplies. To address this knowledge gap, IAH Commission on Managed Aquifer Recharge and UNESCO are establishing a MAR-NET network of centres of national concentration of expertise in managed aquifer recharge with associated demonstration projects to provide training in this aspect of groundwater management which seriously lags our competencies to extract water from aquifers. The network will lead to efficient exchange of information, teaching resources and facilitate expertise from a range of disciplines to be brought to bear. Meetings would be useful between the ISMAR series of conferences, the latest of which was in Beijing 15-19 Oct 2013 (http://www.ismar8.org).

4.2 Scope and potential for managing and improving groundwater storage and recovery

It is evident that groundwater policy reform is required, and that entitlement to groundwater through land ownership or prior right does not work and cannot work in slowing or reversing groundwater depletion. These methods have conspicuously failed to allow volumetric allocations to be modified equitably, as the environmentally protective allocatable resource pool becomes better defined. Furthermore, they oppose maximization of the utility of the groundwater resource. Like the monkey unable to retrieve its hand from the jar without releasing the fruit, unless these systems are abandoned there is no hope of an acceptable outcome.

Improving irrigation efficiency and agronomic methods can reduce water use while sustaining or enhancing production. This should be considered in every portfolio of groundwater management policies. Improved awareness of the magnitude and degree of resilience of the groundwater resources will help communities understand that the resource is finite, shared and that there are severe consequences to all groundwater users and to connected streams and ecosystems if too much groundwater is extracted.

The key issue is for all groundwater users to understand they are sharing a common good, and that there is a finite limit to the total that can be shared. Two distinct and quite separate processes are required;

(1) a scientific assessment of the magnitude of the allocatable resource, repeated periodically, based on credible monitoring of the groundwater storage and water use;

(2) a socially acceptable way for shares (entitlements) in that allocatable resource to be allocated to groundwater users, taking account of social, environmental and economic factors.

Allocations are made for a period, based on multiplying the currently determined allocatable resource by the share of each groundwater user. Shares and allocations should be transferable. They should be registered as a property right and traded in an open market, subject to rules to protect the environment and other groundwater users.

Legislation may be required to vest the groundwater resource in the ownership of the State. Groundwater users recognize they have only an ambit claim to a continued right to the volume of groundwater previously attached to land ownership, as that volume will not be available unless total demand on the system is to reduce. However, these users are taken into account in assigning shares of the allocatable resource.

In the event that there is disagreement among users, historical uses only should be taken into account, the shares of an individual should be based on the ratio of their historical use to the sum of historical uses of all individuals over a period concluding before share apportionment is calculated. Intended new users of groundwater would need to buy their allocation from a willing seller on the market at the price they agree.

Demand management is a key element for sustaining groundwater supplies, and where other water resources are available, this can be assisted by managed aquifer recharge and supply augmentation. These additional measures can be applied most effectively where there is an entitlement system for groundwater use. For example, new or existing groundwater users may be able to pay for managed aquifer recharge systems through the sale of some of the allocations that MAR may yield. Similarly, if supply augmentation with surface water systems occurs, entitlement to access this water may require foregoing groundwater entitlements so as to ensure there is a benefit to the aquifer (as was required in Bangkok).

There are potentially significant benefits in incorporating managed aquifer recharge and/or supply augmentation where the costs of these options in monetary units per volume of water are less than the equivalent cost of reducing production. There may be additional benefits where otherwise wasted water from urban areas or industries is harvested and treated to make it compatible with the aquifer and with the existing uses of groundwater. Development of expertise is needed to capture these opportunities.

A framework for incorporating managed aquifer recharge into water resources management policies is presented by Ward and Dillon (2011) (Table 3). It consists very simply of applying the three instruments – entitlements, allocations and use conditions – to each of the four key elements of managed aquifer recharge; access to recharge water, recharge, recovery and end use. It includes a recommended practical procedure, including constraints on trading of recovery credits. This may be used to facilitate groundwater users associations, and provide a way of sourcing investment in managed aquifer recharge by beneficiaries across the groundwater basin.

Table 3. Natural resource management for MAR based on the robust separation of rights (from Ward and Dillon, 2011)

MAR governance instrument:	Source Water Harvesting	Recharge	Recovery	End Use
Entitlement	Unit share in surface water, stormwater or effluent consumptive pool (i.e. excess to environmental flows)	Unit share of aquifer's finite additional storage capacity	(Tradeable) extraction share, which is a function of managed recharge	N/A
Periodic allocation	Periodic (usually annual) allocation rules. Potential for additional stormwater or treated effluent subject to high flows or development offsets	Annual right to raise the water table or piezometric head subject to natural recharge and total abstraction	Extraction volume contingent on ambient conditions, natural recharge and spatial constraints	N/A
Obligations and conditions	Third party rights of access to infrastructure for stormwater and sewage	Requirement not to interfere with entitlements of other water users and water bankers	Existing licence may need to be converted to compatible entitlement to extract (unit share)	Water use licence subject to regional obligations and conditions, for use and disposal

N/A = not applicable

The entitlement to recover a volume of water which relates to water that has been recharged to an aquifer water in general should be tradeable, but with constraints on trading entitlements into drawdown cones or trading into parts of aquifers that are fresher than the water being recharged. A set of entitlement descriptions is given in Table 4 based on the hydraulic retention time of the aquifer and whether the aquifer is already over-allocated. Further information is found in Ward and Dillon (2011 and 2012).

Table 4. Recovery entitlement descriptions for different aquifer characteristics (from Ward and Dillon, 2011)

	Over-exploited aquifer		Aquifer in equilibrium	
	Long hydraulic retention time T[a] T>30 years	Short hydraulic retention time T T<30 years	Long hydraulic retention time T T>30 years	Short hydraulic retention time T T<30 years
Maximum cumulative % recovered *	90% (S)	90% (S)	100% (S)**	100% (S)**
Time period for Recovery (years)	30	T	30	T
Depletion rate for stored water (%) *	0 (S)	100/T (S)	0 (S)	100/T (S)
Maximum recovery in any year	<max annual recharge	<max annual recharge	-	-
Transfers permitted	yes	yes	yes	yes

[a] T represents the hydraulic retention time of recharged water.

* Maximum percent recovered in a brackish aquifer is constrained by the salinity (S) of the recovered water needing to meet the requirements for its use. Recovery ceases when water reaches this salinity threshold or the percentage constraint whichever occurs first.

** In some brackish aquifers, the salinity constraint may not be reached until recovery significantly exceeds 100% recharge. In such cases the MAR operator could apply for entitlement to native groundwater for the amount in excess of their recovery credit (100% recharge volume).

4.3 A unifying synthesis

Principles and high-level frameworks for groundwater management approaches have been presented with emphasis on community based management (Wegerich, 2005) and integrated water resources management (Forster and Ait-Kadi, 2012). In harmony with these but at a lower level, a unifying synthesis of groundwater management success reported in this thematic paper is illustrated diagrammatically in Figure 15. This illustrates pathways through policy reform that have been shown to be successful in achieving agreed objectives for unstressed and stressed aquifers. This takes account of stakeholders' capabilities for collective action and the prospects for managed aquifer recharge or water-supply augmentation in concert with demand management, where alternative water resources are available.

While a number of case studies have been highly successful in achieving objectives that account for economic, social and environmental objectives, few case studies have embraced a holistic governance arrangement that enable synergistic effects of managing recharge and discharge in concert. The strategy, together with stepwise pathway, is intended to serve as a basis for designing national investment programmes related to groundwater-equilibrium management.

Cost sharing between government and groundwater users may be used as a lever to implement reform. Where this is possible, government investment may depend on groundwater users' contributions to efficiency measures and reduced use, alternative supplies, managed aquifer recharge and other groundwater management costs. Users' share of costs would be in proportion to their share of entitlements to the allocatable resource.

If groundwater users are unable to make a contribution, this may in some circumstances suggest that the value of their crops grown with groundwater is low. A virtual water perspective on the efficiency of growing those crops in wetter areas, even outside the country, may show that there is higher value to be obtained by switching to other crops or not irrigating to prolong or sustain the availability of water to support crops with higher value per cubic metre of water used. A cap-and-trade system will allow transfer of cash from water buyers with high-valued crops to those exiting irrigation farming of crops with low value per cubic meter of water used. In some cases, the return on sale of water allocation would exceed the net revenue for growing a crop, and would assist in establishing new low water-use enterprise or relocation.

Fig 15 illustrates a pathway forward for a range of circumstances, to prevent over-allocation where aquifers are able to supply existing irrigation and other water-supply demands without environmental or ecosystem degradation. It also aims to develop capability for collective management where it does not already exist, so that communities are informed and empowered. Where over-allocation already occurs, there needs to be an assessment of whether other sources of water are available, allocatable and economic, for managed aquifer recharge or to substitute for groundwater use. These may include surface water from catchments, even if only intermittently in excess of environmental flow requirements, and treated urban runoff and sewage, backed by water quality management with water safety plans enacted, including monitoring and treatment. Combinations of demand reduction, managed aquifer recharge and alternative supplies may then be identified, prioritized and sequentially implemented. Normally improving irrigation efficiency will be the highest priority activity. In the absence of alternative supplies, demand-reduction measures, combined with periodic assessment of the prospective lifetime of the resource will allow planning for transition from agriculture to low-water use livelihoods, including industrial and commercial enterprises. To compensate, food production would need to be enhanced in other locations where water is more plentiful.

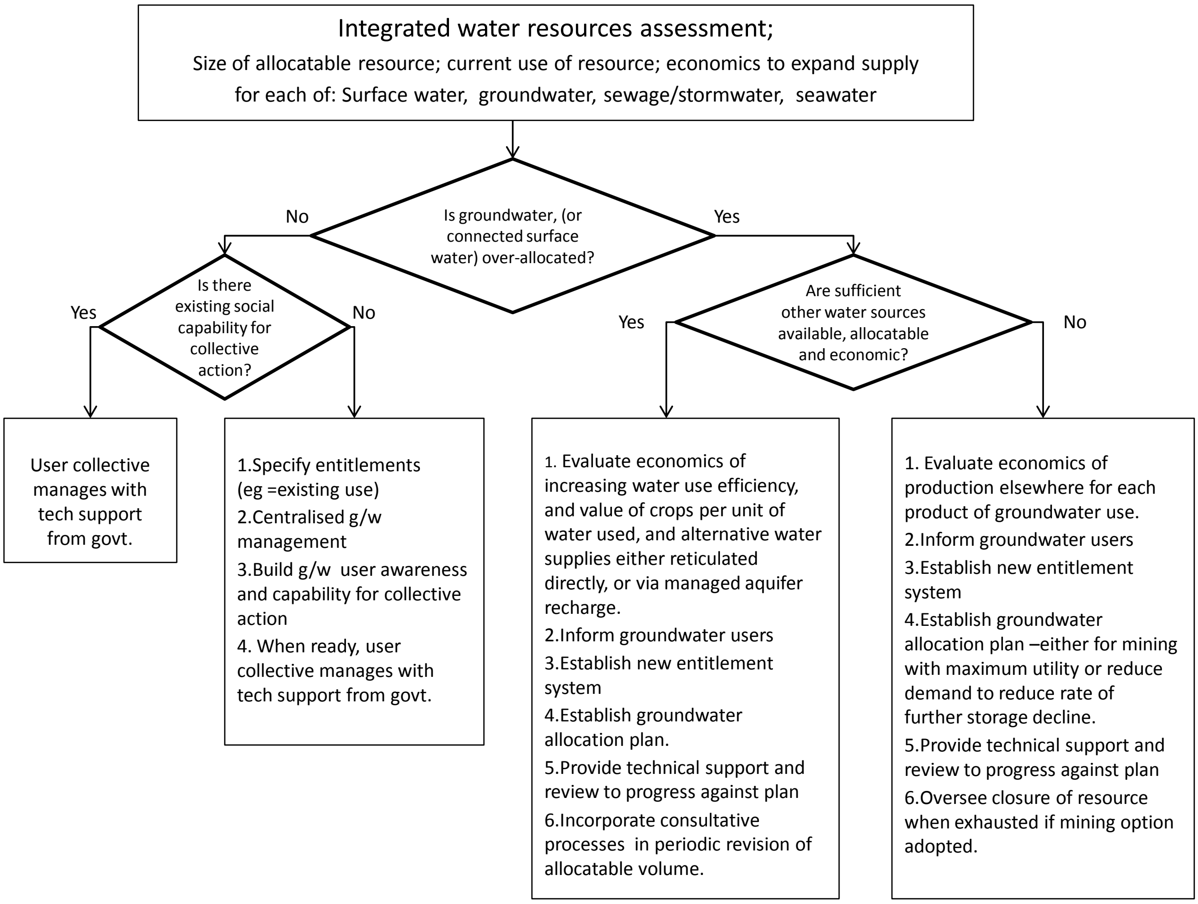


Figure 15. A decision tree to illustrate pathways through policy reform that have been successful in achieving agreed objectives in stressed and unstressed aquifers

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Appendix A

Combined effectiveness of demand management and managed aquifer recharge to address aquifer depletion (extract from Dillon et al. 2009b)

The likely effectiveness of managed aquifer recharge to address groundwater over-exploitation may be determined approximately by conceptualising the irrigation demand and aquifer properties and levels as uniform and with the same spatial extent. Assuming that the storage (S) accessible to irrigation wells in the aquifer is homogenised over the irrigation area, then if extractive discharge (D) expressed as mm/year exceeds the rate of recharge R_n (natural recharge plus deep seepage), then the average number of years (T) before yield failure occurs will be given by:

$$T = S / (D - R_n) \tag{1}$$

If managed aquifer recharge is expressed as an effective rate R_m over the irrigation area, and groundwater discharge management methods reduce discharge by D_m then the intent is to attain an equilibrium (where $T_m \leq 0$). However, less effective efforts serve to prolong the average number of years ($T_m > 0$) before yield failure occurs as given by equation (2):

$$T_m = S / ((D - D_m) - (R_n + R_m)) \tag{2}$$

where D = discharge (pumping for drinking, irrigation, industry) (mm/year); D_m = reduction in discharge due to demand management (increased irrigation efficiency, substitution of surface supplies or restrictions on groundwater use) (mm/year); R_n = natural rate of recharge and including irrigation deep seepage (mm/year); R_m = effective rate of managed aquifer recharge (mm/year); S = storage accessible before yield failure (mm) =accessible saturated thickness* porosity; T = years until yield failure if $D > R_n$ (no failure otherwise as not over-allocated); and T_m = years until yield failure if $(D - D_m) > (R_n + R_m)$ (no failure otherwise as management is effective in sustaining yield.)

The prolonging of irrigation in an over-allocated aquifer by managing aquifer recharge and discharge is therefore given by:

$$T_m / T = 1 / (1 - (R_m + D_m) / (D - R_n)) = 1 / (1 - r - d) \quad \text{for } r + d < 1 \tag{3}$$

where $(D - R_n)$ = annual deficit = rate of over-exploitation; $r = R_m / (D - R_n)$ = proportion of deficit addressed by recharge enhancement; and $d = D_m / (D - R_n)$ = proportion of deficit addressed by discharge reduction.

Hence there are three management scenarios for restoring an over-allocated aquifer to hydrological equilibrium:

(1) where managed aquifer recharge alone is able to overcome the deficit, (i.e. $r \geq 1$);
(2) where demand reduction alone is sufficient to restore hydrologic equilibrium (i.e. $d \geq 1$), and
(3) where the combination of managing aquifer recharge and discharge is able to restore hydrological equilibrium (i.e. $r + d \geq 1$).

Table B.1 Effectiveness of MAR in combination with demand reduction in over-exploited aquifer example expressed as years to yield failure, T_m.

$r = R_m/(D - R_n)$	$d = D_m / (D - R_n)$					
	0	0.1	0.2	0.5	0.8	1
0	20	22	25	40	100	∞
0.1	22	25	29	50	200	∞
0.2	25	29	33	67	∞	∞
0.5	40	50	67	∞	∞	∞
0.8	100	200	∞	∞	∞	∞
1	∞	∞	∞	∞	∞	∞

Consider a simple worked example of an aquifer 20-m thick with an effective porosity of 0.1 giving an accessible storage, S of 2 000 mm. If the excess of demand over natural recharge replenishment ($D - R_n$) is 100 mm/year then from equation (1) the expected irrigation lifetime of the aquifer (T) is 20 years. To sustain the system either 100 mm of recharge enhancement, 100 mm of discharge reduction, or a combination of recharge enhancement and recharge reduction totalling 100 mm is required. The extent to which irrigated production could be prolonged by combinations of recharge enhancement and discharge management for this example are shown in Table 1.

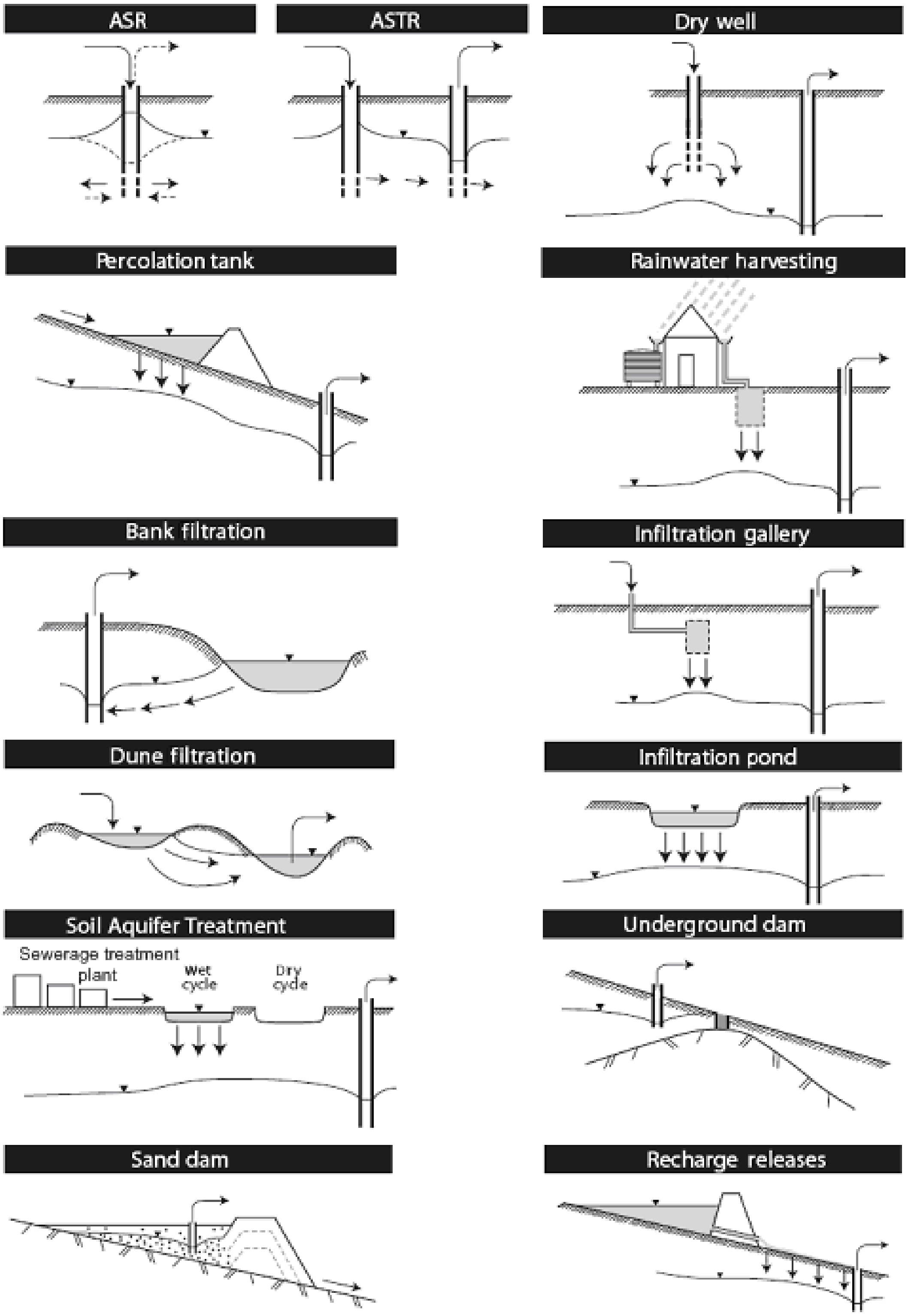
Appendix B

Characteristics of aquifers and their influence on potential for managed aquifer recharge (adapted from Dillon and Jimenez, 2008)

Characteristic	Feature and influence on managed aquifer recharge	
Permeability	Moderate to high • High rates of recharge possible • Recharged water can be dispersed • Lower capital and energy costs per unit of water recovered	Low to moderate • Lower rates of recharge possible • Recharged water more localized • Greater capital and energy costs per unit of water recovered
Confinement	Unconfined • Surface infiltration methods viable • Unprotected from surface contamination • Storage capacity depends on depth to water table	Confined • Well injection methods only • Protected from surface contamination • Storage capacity depends on aquifer thickness
Thickness	Thick • High storage potential • More sensitive to salinity stratification if native groundwater is brackish	Thin • Low storage potential • May limit rate of recovery by wells
Uniformity of hydraulic properties	Homogeneous • Minimal mixing and higher recovery efficiencies if native groundwater is brackish	Heterogeneous • Lower recovery efficiencies if native groundwater is brackish • In karstic and fractured rock systems, limited ability to contain recharged water
Salinity of groundwater	Fresh • Recovery efficiency not limiting • Requirement to protect wider range of beneficial uses of aquifer (higher treatment costs)	Saline • Recovery efficiency can limit effectiveness • Less beneficial uses to protect, so treatment need be less onerous
Lateral hydraulic gradient	Gentle • Recharged water contained closer to point of recharge	Moderate to steep • Recharged water dispersed down-gradient and lower recovery efficiency in saline native groundwater
Consolidation	Consolidated • Easier to complete wells • Easier to maintain recharge wells to prevent irrecoverable clogging	Unconsolidated • Screens required for injection and recovery wells • Land subsidence a consideration
Aquifer mineralogy	Unreactive with recharge water • Recovered water quality unaffected by geochemical reactions with aquifer matrix • Likelihood of clogging of injection wells is sometimes increased	Reactive with recharge water • Consider metal (e.g. arsenic) mobilization, iron and H_2S effects on recovered water and groundwater • In carbonate aquifers, less onerous treatment required to avoid clogging of injection wells
Redox state of native groundwater	Aerobic • Higher rates of inactivation of pathogens and biodegradation of some endocrine disrupting chemicals	Anaerobic • Higher biodegradation rates for trihalomethanes

Appendix C

Schematic of types of managed aquifer recharge (adapted from Dillon, 2005).



Groundwater Policy and Governance

Digest

Groundwater governance — The overarching framework

Groundwater governance is the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels -– one of which may be global. In practice, groundwater governance is the complex and over-arching framework that determines the management of groundwater resources and the use of the aquifers. The local, regional or national governance framework establishes "who" participates in formulating strategies and is responsible for their execution and "how" the different actors (governmental, public sector, non-governmental, private sector, and civil society) interact. **Water management** is "what" we do. It consists of the activities that enable us to move toward achieving goals and objectives. Examples of activities include pumping wells, substituting surface water for groundwater, aquifer recharge, and irrigation practices or other approaches to more efficient water use. Examples of a goal or objective are sustainable water use and maintaining ecosystem health.

Key points for decision makers and the broader public

Governance entails responsible resource use, leading to environmental and economic sustainability; sensitivity and adaptation to geography and environment, customs, cultures, political systems, and prevailing practices. Strong stakeholder participation and social acceptance are keys to acceptability of governance practices. Equitable access to water, fair distribution of costs and benefits, and attention to preferences and to winners and losers are critical concerns.

Approaches include those by the UN Development Program, the Millennium Ecosystem Assessment, and the Global Water Partnership — via integrated water resource management (IWRM). Principles of good groundwater governance fall into four main sets of principles and considerations. (1) Political and institutional: Accountability, representation, consistency, match of scale, institutional match, and institutional capacity to adapt to uncertainty and change. Groundwater is mostly a local issue and solutions need to fit institutionally and socio-culturally — recognizing that paradigms and social constructs change over time. (2) Sociocultural: Perceptions about groundwater, religious and spiritual traditions, social learning, social inclusion, ethics, multi-level/multi-scale/polycentric governance models. (3) Economic: Imperfection of price signals, the role of scarcity and groundwater-storage conditions, water-quality impacts, inadequate measurement of groundwater usage rates, the growing role of the private sector and public-private partnerships, and the importance of ability to pay. In addition, water prices may not fully reflect the costs of extraction, and rarely include third-party and environmental impacts of groundwater use. Economists often see market mechanisms as having potential to match demand with supplies. (4) Ecological: Physical characteristics of diffusivity, conduciveness, attenuation rates and renewability. In addition, groundwater development may rival existing land uses. Groundwater systems can be considered common-property resources, vulnerable to over-exploitation and/or under-management. Aquifers are coming to be valued not only for their provisioning services (for consumption, agriculture, or industry) but also for their ecosystem-supporting services.

Additionally, the *spatial and temporal contexts* determine the applicability and potential success of governance and management instruments. Often, state-, market- and collective-action-driven groundwater-governance paradigms have been practiced simultaneously in hybrid or nested form. Improved groundwater governance practices depend on accepting the complexity and diversity of groundwater-resources management modes. The following are important considerations. *Legal dimensions* are likewise important. Groundwater use is dependent on a host of legal instruments, such as: existing formal and customary rights regimes; legislation that specifies access, allocation, and quality; regulations that control planning and zoning; laws and statutes that protect recharge areas, potable water sources, riparian corridors and habitats, and endangered species; enforcement directives; pricing and use regulations; mandates for public participation and transparency; and international treaties, agreements, and protocols. By shaping public policy, these legal instruments influence the nature and details of governance within a nation's boundaries and beyond. Of course, the *physical dimensions* must be considered. Water is fluid. Its flow patterns do not follow the political boundaries associated with a given jurisdiction's laws and regulations. Given this fluid nature and fluctuations in its availability, water resources require active management. The governance of groundwater basins can present conditions different from river systems, which are important to the development of governance frameworks.

Improvements to groundwater governance will require *new approaches.* The classic, techno-physical, top-down approach presumes an ability to identify and quantify the nature of interactions and clearly define the boundaries of systems. It also assumes that for social institutions (like rules and rights systems), sufficient organizational capacity exists to permit planned and integrated implementation. The "good governance" framework emphasizes sustainability, market approaches, and decentralization. The paradigms of groundwater governance are assumed to be nested within those that govern water generally, which are part of the larger picture of how we deal with natural resources in general.

Case studies

Case studies of domestic and transboundary groundwater management are useful to understanding the advantages and drawbacks of alternative approaches and experiences. The paper includes several case studies. A set of broad barriers to groundwater governance was identified: inertia and resistance to change, rent-seeking behaviour, problems of fit, problems of interplay, information deficit, poor framing of groundwater issues, and insufficient public participation. Other limitations include incomplete knowledge about: complex and heterogeneous groundwater resources, socioeconomic and demand information, connections between the water sector and macro-policies (e.g., food and energy security) in a given national context, institutional diversity and management practices, and evolving effects of global connectivity.

Significant prospects and recommendations

Technical and scientific approaches have enriched our understanding of and provided ways to harness groundwater systems. But attention to governance has revealed that the chief constraints are social, institutional, and political. Innovations in groundwater governance can induce changes in power relations and incur high transaction costs. They may best be developed incrementally.
Ideally, groundwater management and policymaking should be performed at the level appropriate for the context, which is often local. Decentralized management, with stakeholder participation and coherence across scales is the most promising approach. Groundwater governance also should consider national and international food- and energy-security policies. Optimizing demand can have larger effects than sophisticated water-saving measures. But reduction of demand should be balanced with potential loss of agricultural livelihoods and economies. Broad criteria for effective groundwater governance include: creation of *common property regimes* or "unitization" agreements at the aquifer scale; *mediation and conflict resolution* for international aquifers; *voluntary compliance*; *flexible and adaptive management*; and *policy diversification*.

The paper includes several sets of recommendations. Government agencies should shift from 'supply-development' to 'resource-custodian' and 'information-provider,' with agencies fully engaging groundwater users and stakeholders in a participatory-management process. National governments should ensure strong state/provincial level agencies by supporting professional development, establishing management guidelines for shared aquifers, and providing monitoring standards for at-risk basins. Water-management responsibilities might be realigned within ministries of environment and other agencies to maximize influence to negotiate with more powerful entities (*e.g.* ministries of finance, agriculture, or industry). Policymaking could be separated from the operational management of water services. Institutional processes should be explored to remediate bureaucratic inertia and political reluctance. Links can be made to larger macro-level policy decisions (*e.g.* on food, energy, and trade). Comprehensive review of policy and legislation might examine existing frameworks and identify appropriate policy and legislative modifications.

Development of national information and science programs to gather data in areas where groundwater dependence is high should be encouraged. Opportunities include using remote-sensing images to estimate surface components of groundwater systems such as recharge and discharge to support groundwater-resource managers; collecting relevant socioeconomic information; and overcoming institutional asymmetries so as to facilitate negotiation and conflict resolution. The international community, acting through bilateral and multilateral aid mechanisms, should assist with data-collection and management support. In countries that lack basic hydrological data, a greater investment in data collection and data management will be necessary. Additionally, early warning systems based on indicators to assist with disaster-preparedness are important because institutional capacity is absent in many countries. Finally, global water initiatives such as IHP and GWP need to disseminate these modes of information acquisition and sharing.

Public participation is essential for ensuring that governance practices meet the goals of transparency and accountability. Since groundwater management is largely about influencing user and polluter behaviour, enabling and nurturing stakeholder participation is an especially critical groundwater governance instrument. Leadership in groundwater governance is essential for planning and implementation, facilitation of communication, and support of information exchange. Other suggestions include training NGO staffs and citizen groups on technical groundwater issues and on policymaking techniques, developing and enabling community-management of groundwater resources, and applying modern information technology to better connect stakeholder groups and form communities of practice.

Scale is important in several respects. The impact of existing and proposed macro-policies on water development and use should be continuously analyzed. National governments can promote bottom-up approaches by mobilizing citizens, providing funds and technical services for local initiatives, investing in infrastructure, building capacity and expertise among practitioners, and coordinating initiatives that span multiple levels of government. Greater coherence might be built across scales; to better achieve vertical integration of governance systems across levels, water management should be coherently addressed by local action, national policies, and international agreements. Global policy networks could help achieve smarter horizontal governance approaches. Finally, new bridging organizations might help manoeuvre between scales, and international groundwater initiatives might play an intermediary role and promote the co-production of knowledge.

Economic considerations are key determinants of behaviour. Economic incentives can steer individual users' behaviour as well as institutional behaviour. Careful attention should be given to developing best-practices guidelines for water pricing in order to incorporate the scarcity value of water and for recognizing third-party impacts. In addition, there is the opportunity to improve water allocation through the deployment of market approaches, so long as they are accompanied by corresponding oversight.

Concluding observations

All modes of tapping, distributing, and managing water supplies result from organized human effort. Responsible groundwater use will require practices that are flexible, transparent, responsive, incremental, cost-effective, culturally sensitive, equitable, and politically astute. To the greatest degree possible, groundwater governance should be context-based and adaptive. Long-term sustainability of groundwater management will require each country to govern its water resources within its own financial, technological and institutional capability, as well as to use strategically available international resources. All this calls for considerable ingenuity at the appropriate governance levels to figure out the most appropriate ways of proceeding in specific contexts.

Thematic Paper No. 5

GROUNDWATER POLICY AND GOVERNANCE

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Acronyms used

CABI – Commonwealth Agricultural Bureaux International
CBO – community based organization
CGG – Commission on Global Governance
DWA – Department of Water Affairs (South Africa)
EA – Environmental Agency (UK)
EIA – environmental impact assessment
EPA – Environmental Protection Agency (US)
FAO – Food and Agriculture Organization (UN)
GEF – Global Environment Facility
GMA – Groundwater Management Act of 1980 (Arizona, US)
GoG – Government of Gujarat (India)
GWG – Groundwater Governance Project (GEF)
GW-MATE - Groundwater Management Advisory Team
GWP – Global Water Partnership
HWRP – Hydrology and Water Resources Program (World Meteorological Organization)
IAH – International Association of Hydrogeologists
IHD – International Hydrological Decade
HLPE – High Level Panel of Experts
IHP – International Hydrological Program (UN)
IIED – International Institute for Environment and Development
IWRM – integrated water resources management
ISARM – Internationally Shared Aquifer Resources Management Initiative
MA – Millennium Ecosystem Assessment
NGO – nongovernmental organization
NWA – National Water Act of 1998 (South Africa)
NWSAS – North Western Saharan Aquifer System
OECD – Organization for Economic Co-operation and Development
OSS – Observatoire du Sahara et du Sahel
UN – United Nations
UNDP – United Nations Development Programme
UNECE – United Nations Economic Commission for Europe
UNEP – United Nations Environment Programme
UNESCO – United Nations Educational, Scientific and Cultural Organization
WGF – Water Governance Facility (UNDP)

1. Introduction

Governance is an immense conceptual construct, encompassing a suite of precepts, principles, ideas, theories, contexts, objectives, and practices. The FAO/ GEF project "Groundwater Governance: A Global Framework for Country Action" is a comprehensive attempt to understand and articulate this notion in its entirety—as applied to the particular subject of groundwater.

The present paper, whose focus is the *policy aspect of groundwater governance*, proceeds from the following set of basic understandings:

- Groundwater is far-and-away the largest source of freshwater in a world where many regions worry about critical shortages
- In the recent past, the study and management of water in general, and groundwater in particular, have benefited from a more well-rounded, more forward-looking, and more comprehensive set of principles and tools
- Non-technical, "soft" approaches to managing water have accepted the centrality of understanding modes of governance. The present water crisis—insofar as the growing lack of access to potable water and water for agricultural and industrial use can be described in such alarming terms—is "mainly a crisis of governance," the Global Water Partnership proclaimed at the turn of the current century (Mukerjee and Shah, 2005).
- Ultimately, principles of governance (which are reviewed and elaborated in this paper)—to the extent that they are appropriate—can result in the development and implementation of effective policies, and
- Such policies can yield a set of practices for "responsible groundwater use," including equity, sustainability and efficiency considerations.

PART 1: BASELINE

2. Policy Framework

2.1 Context

Over the past two generations — and especially since the pioneering 1972 UN Conference on Human Environment and then the 1977 Mar Del Plata UN Conference on Water — public attention has been drawn to the significance of water as the key to human sustenance. Always present implicitly, historically water was perceived as an ingredient for agriculture, transportation, industry, and human development. But when water was studied explicitly, it was typically by hydrologists, civil engineers, and chemists who sought to know its properties, characteristics, and potential for irrigation and power. And nearly always, visible water — that is, surface water — was the main subject of inquiry.

Water science, or more generally, water studies came to be synonymous with investigations of the world's rivers, lakes, oceans, and glaciers. With the convening of the International Geophysical Year (1957-58), and then of the International Hydrological Decade (IHD; 1965-74), these resources were subjected to intensive study. Scientists from both sides of the Cold War divide joined to map river and irrigation systems, estimate water budgets, calculate potential hydrokinetic power, compile glossaries, and propose research protocols. By the end of the IHD and with the 1975 creation of the UN's International Hydrological Programme (IHP), physical scientists had considerably increased general knowledge of the geography, mechanics, and composition of the planet's surface water (Varady, *et al.* 2008).

But there remained large gaps in our understanding of the role of water in society-at-large and its interconnectedness to the Earth's environment. It was not until the advent in the late 1980s and the subsequent acceptance of the notion of (environmental) sustainability that water became recognized explicitly as a critical resource and core value. Along with sustainability came a number of corollary precepts that have gained currency:

- Integrating water management within other aspects of socioeconomic development is indispensable (*viz.* IWRM, or Integrated Water Resources Management; Rogers and Hall, 2003)
- "Context matters," as Elinor Ostrom (1990) has written, and one-size-fits-all solutions are illusory
- The involvement of non-state actors and diverse stakeholders such as communities in decision-making is a component of most successful resource-management approaches (Biermann and Pattberg, 2008)
- Expertise should be harnessed across a full spectrum of disciplinary approaches, including the social sciences and law
- Communities of practice, such as those among government authorities, scientists, and water users are catalysts for effective management of resources (Ross and Martínez-Santos, 2010)
- Hegemonic, equity-related, ethical, and other political motives are key factors in national, international, and transboundary matters (Gerlak *et al.*, 2011)
- Governance and the globalization of water governance have become increasingly prominent elements of the management discourse (Varady *et al.*, 2009)
- The change in thinking about environmental governance is most clearly visible in the new attention that market-based approaches have received (Agrawal and Lemos, 2007; Barraqué, 2004)
- "Demand-side" management of water and other resources is as critical as supply augmentation in attempting to ensure sustainability across future generations (Hutchinson, et al., 2009)
- Beyond financial and hydrological considerations, key obstacles to improved management include extensive institutional and territorial fragmentation in a sector with numerous stakeholders at different levels; and strong spillovers in other policy areas such as agriculture, spatial planning, and energy (OECD, 2011).

During this same period of transition from a top-down, techno-physical, and present-centric orientation to a more bottom-up, holistic, future-oriented one, another realization became manifest: that in spite of what our eyes were telling us, the vast majority of world's freshwater was not above the ground, but below it. An early proponent of this revisionist view was the International Association of Hydrogeologists (IAH), which was established in 1964 by hydrologists who were convinced of the distinctiveness and importance of groundwater. Although some irrigation-intensive regions of the world like the Punjab in India and Pakistan had begun shifting from river water to groundwater by the 1960s, the amount of groundwater on the planet was not well understood and vastly underestimated. Now we know that — if polar ice and glaciers are not included in surface water amounts — groundwater systems hold as much as 98 percent of the total freshwater on Earth (Foster and Chilton, 2003). And in developing countries, especially, exploitation of these below-the-surface sources has been accelerating rapidly since 1970, accounting for half of India's agricultural water use and as much as two-thirds in parts of China (Giordano and Villholth, 2007).

2.2 Existing legal frameworks for groundwater allocation and management

It is evident to students and observers of governance that national and international laws are critical instruments for designing and implementing public policy. In fact, confronting the on-the-ground challenges of actually implementing groundwater governance requires close attention to the legal frameworks that prevail in a given context.

As with surface water use, groundwater use is highly dependent on a host of legal institutions, such as:

- Existing formal and customary rights regimes
- Legislation that specifies access, allocation, and quality
- Regulations that control planning and zoning
- Laws and statutes that protect recharge areas, potable water sources, riparian corridors and habitats, and endangered species
- Enforcement directives
- Pricing and use regulations
- Mandates for public participation and transparency, and
- International treaties, agreements, and protocols

By shaping public policy, these legal instruments wield tremendous influence on the nature and details of governance within a nation's boundaries and beyond (Nanni *et al.*, 2006; Eckstein, 2011; McCaffrey, 2011). Thematic Paper No. 6 in this series, "Legal Frameworks for Groundwater Governance," offers far greater detail on this subject and we have relied on the working outline for this paper (Mechlem *et al*., 2011).

3. Current Definitions of Groundwater Governance – a Typology

Consider the simple term 'governance': a review of definitions provided by 12 respected sources[1] offers up some three dozen keywords[2], each of which has a place among the elements defining governance. Contributing to the fuzziness of the idea, each set of authors appears reluctant to assert unequivocally: "governance *is*. . . ." Instead, they dance around the subject, employing such phrases as: "governance *describes/is described as/emphasizes/encompasses/ is about/is an arena in which/is characterized by/refers to/relates to. . . .*"

For the World Bank (1991), governance is, simply put, "the exercise of political authority and the use of institutional resources to manage society's problems and affairs." The definition is pithy, but it lacks the richness that has propelled governance to the fore of so much discussion. For the purposes of this paper, we like the direct and nuanced definition of governance provided by Saunier and Meganck in their *Dictionary and Introduction to Global Environmental Governance* (2007). Below, we have adapted their statement to serve as our working definition:

> Groundwater governance is the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels-–one of which may be global.

To this definition, Saunier and Meganck add a useful thought formulated in 1995 by the Commission on Global Governance, "Governance is the sum of the many ways individuals and institutions, public and private, manage their common affairs." Importantly, governance implies a <u>process</u> by which societies govern (Lautze *et al*., 2011).

[1] Batterbury and Fernando 2006, Biermann and Pattberg 2008, Beall 2005, Hyden *et al.* 2004, Knueppe 2011, Linton and Brooks 2011, Nowlan and Bakker 2010, Ostrom 2005, Rogers and Hall 2003, Ross and Martínez-Santos 2010, Theesfeld 2008, and Turton *et al.* 2006.

[2] Accountability, allocation, authority, civil society, coherence, conflict, decisions, decision-making, duties, formal, influence, informal, institutions, laws, levels, markets, mitigation, models, networks, non-state actors, objectives, officials, outcomes, politics, polycentric, principles, private sector, regulation, relationships, rights, rules, scale, security, stewardship, sustainability, tradeoffs, users.

4. Groundwater Governance, Policy and Management

4.1 What are the distinctions?

The present essay, one of a set of thematic papers commissioned by the GEF-financed Groundwater Governance project, addresses the topic of policy. For our purposes, it is essential to distinguish among a number of fundamental, interrelated terms and concepts: governance, management and, of course, policy. A survey of recent literature on these notions — which as noted have gained prominence in the discourse on natural resources and water — reveals what appears at first glance to be a cacophony of terms struggling to converge to a coherent concept.

Management: The term 'management' is perhaps easier to grasp intuitively than its more layered and ambitious cousin 'governance.' We tend to think of management as the "nitty-gritty of day-to-day operations" that emphasize the results of decisions (Linton and Brooks, 2011). Other similar notions are: "approaches, models, principles, and information used to make decisions" (Bakker, 2007, cited in Nowlan and Bakker, 2010); "regimes based on institutions, laws, cultural factors, knowledge, and practices" (Solanes and Jouravlev, 2006); or purposeful activities that enable the accomplishment of goals and objectives (de Loe and Kreutzwiser, 2005; Pahl-Wostl, 2007), with a common caveat, "by definition, based on conflicting interests" (Wolf, 2007). All these definitions share a concern for routine, practical, and effective ways to achieve predetermined objectives.

Policy: Oddly, as popular and well-ingrained as the idea of 'policy' has become, working definitions are hard to come by. The current edition of the Merriam-Webster Dictionary (2011) defines policy as "a definite course or method of action to guide and determine present and future conditions." The UN's Food and Agriculture Organization (FAO, 2011) favours an even simpler phrase, "a set of decisions which are oriented towards a long term purpose or to a particular problem." The simplicity and succinctness of FAO's definition captures the centrality of the vital term, "decision." For many, including the present authors, policymaking is synonymous with decision-making, and not just by public-sector institutions but by any and all sectors of society, at any level, with a stake in governance.

Once policies have been formulated, putting them in place requires instruments, tools, rules, protocols, and other procedures. These may include laws, sets of rights, registrations, permits, and regulations (especially regulations that allow those regulated to choose among alternative ways of complying); economic incentives and disincentives such as subsidies, taxes, tradable pollution permits, and pricing structures; and civil-society actions such as those that motivate voluntary actions or behavioural changes (Theesfeld, 2008: 6). In this paper we consider policies to encompass all types of decisions used by state and non-state entities.

4.2 How do these concepts relate to natural resources, water and groundwater?

The three concepts discussed above all allow for interpretation and application to nearly any sector of society or government. The elements of educational governance, agricultural governance, and natural resources governance, for example, are broadly similar and accordingly the definition we have adopted for governance is equally valid for each of those domains. Our operational definitions of management and policy also are easily applicable to multiple processes.

For our purposes, policies aimed at groundwater management are a subset of policies targeting water management more generally, and those in turn are nested within still broader policies for managing natural resources and the environment. Leaving aside the important difference that water and environment are less easily commodified as natural resources, the management of all three require analogous approaches.

Not surprisingly, therefore, distinctive features of water governance and groundwater governance are specific to the resource. Given the particular nature of watercourses, repositories, flows, quality, and distribution, managers and decision-makers encounter diverse forms of water — from natural bodies such as streams, lakes, ponds and aquifers, to engineered structures such as canals, barrages, hydropower dams and treatment plants. Given the fluid, fugitive nature of water and natural fluctuations in the availability of the resource, water resources require active management (FAO, 2011: 4). Current thinking holds that effective governance of such complex systems must involve integrated management. It also should have available infrastructure in the form of well-functioning technical, economic, judicial, social, institutional, and administrative structures (Clifton *et al.*, 2010: ix; Knueppe, 2011: 68). In addition, observers agree that good water and groundwater governance entails responsible resource use, leading to environmental and economic sustainability; sensitivity and adaptation to geography and environment, customs, cultures, political systems, and prevailing practices and paradigms; strong stakeholder participation and social acceptance; equitable access to water; fair distribution of costs and benefits; and attention to preferences and to winners and losers (Knueppe, 2011: 68; Linton and Brooks, 2011: 607; Nowlan and Bakker, 2010: 7; Solanes and Jouravlev, 2006: 7-8; van der Gun and Lipponen, 2010: 3430). It is noted that often no universally applicable, measurable and normative definitions exist for above-mentioned notions that good groundwater governance is supposed to lead to — e.g. the difficulty of applying the sustainability concept of because of its multi-interpretability and close relationship with concepts like equity and fairness (UNDP, 2011).

The governance of groundwater basins presents a special condition not present in river systems — e.g. relative to rivers, upstream-downstream considerations are often much smaller as the flow component of groundwater systems is often limited. As Elinor Ostrom (2010) stated recently, "I got started doing my dissertation on groundwater in the early 1960s and didn't know I was studying the tragedy of the commons." It's likely that all groundwater policymakers and managers now recognize that the water contained in aquifers and other subterranean basins is a classic common property resource (see also the section on ecological principles).

4.3 Existing modes of groundwater governance, policy and management

Experts who have studied groundwater use around the world tend to agree that too little is known about the institutions and policies that govern the use of these resources (Mukherji and Shah, 2005). Nevertheless, innovative approaches to groundwater management have been developing in many parts of the world over the past decade (de Gooijer *et al.*, 2009). These approaches, the most notable of which we review briefly in the present section, feature a variety of instruments to manage groundwater (Theesfeld, 2010; Kemper, 2007).

In the past decades, the classical governmental approach towards groundwater resources management has been based on a plan-and-control and engineering-centred approach. In many countries, groundwater management decisions are made and interventions planned in (partly decentralized) governmental entities such as ministries and departments dealing with water resources, agriculture, mining, rural development and, increasingly, departments on urban development and spatial planning and the environment. Often, strongly connected specialist research institutes like geological surveys participate in this approach by providing the necessary data and expert knowledge to develop policies and inform decisions.

The issues that groundwater resource managers must deal with differ depending on the level of groundwater development in their mandated area (Tuinhof *et al.*, 2002). In recent decades, many countries appear to have followed a similar incremental and changing institutional path from initial development to groundwater management. At first, when there is still a need to increase groundwater use in a region and the potential to do so, their work focuses on identifying usable groundwater volumes and supporting supply-side interventions enabling initial access to the groundwater resources. As the level of groundwater abstractions increases, negative consequences may become manifest like falling groundwater tables. To sustain groundwater use in such stressed aquifers, interventions need to be developed that slow down or even reverse aquifer depletion, including the management of groundwater demand and the conjunctive use of surface water. Also, allocation issues then become more prominent due to the rising scarcity. To conserve the productive capacity of aquifers requires constant monitoring of groundwater quantity and quality and includes aquifer protection. Resulting from the notion of the importance of environmental sustainability, some forward-thinking groundwater resources managers have begun to include the management of groundwater-dependent ecosystems as part of their management activities. Aquifer protection policies like those operationalized through the Groundwater Directive of the European Union Water Framework Directive oblige the member states to take measures to avoid aquifers being contaminated by land use activities.

The classic groundwater resource manager's tool-kit consists of a wide set of assessment and planning, controlling, and behaviour-changing instruments, and is based on the existence of various institutions (Tuinhof *et al*., 2002; Kemper, 2007; Theesfeld, 2011). The tool-kit includes (but is not limited to):

- technical instruments (surveying, groundwater quantity and quality monitoring and modelling, other diagnostic analyses, sustainable aquifer yield estimations)
- managerial and planning instruments (IWRM-plans, land use and spatial planning, environmental impact assessment, groundwater protection zoning, clear definition of responsibilities and roles of various groundwater resources management entities)
- regulatory instruments (groundwater property and usufruct rights, well licensing and registering, drilling accreditation, water legislation, groundwater caps, bans on hazardous human activities with risks of groundwater contamination)
- economic instruments (groundwater pricing, environmental taxes, tradable rights and groundwater markets) and behaviour-changing instruments (training, information sharing).

Moench *et al.* (2003) argue that this classic approach presumes an ability to identify and quantify the nature of interactions and to clearly define the boundaries of systems. It also presumes that for social institutions (like rights systems and regulatory organizations), sufficient organizational capacity is available so that implementation can occur in a planned and integrated manner.

It needs to be noted that this formalized type of groundwater management is a relatively recent institutional phenomenon. Certainly in the United Kingdom, it was not until the Water Resources Board was formed in 1964 that groundwater became an explicit part of national water policy. In the United States, state water laws had a different set of inception points in the 20th century as water scarcity became manifest, as in other post-industrial countries. However, this does not imply that before the 20th century groundwater management was totally non-existent in these or other countries. Nor does it mean that there was a total absence of governmental interference.

Many historical and more recent examples exist where bottom-up approaches towards water management have been working well. Most of these approaches have been in the field of surface water irrigation but groundwater examples exist as well. Some of the historical case studies described in section 7 and the ancient remnants of rather complicated water infrastructure like qanat systems in former Mesopotamia or related to ancient Indian cultures in South America indicate that complicated systems of more formal or informal (ground)water management must have been existent throughout human civilization. Extensive work by the Ostrom school managed to distil various factors that foster or limit such approaches like the level of salience, homogeneity of users groups and the existence of effective conflict resolution mechanisms.

5. Principles that have been applied in Water Governance Models

Since the 1990s, following larger trends in development, the more centralized, state-led development model for water resources has been replaced by a model of "good governance" that emphasizes sustainability, neo-liberal and market approaches, and decentralization (Varady et al., 2008; Batchelor, 2007; Moriarty *et al*., 2004; Cook and Sachs, 1999; Conca, 2006). This shift in governance has been referred to a "scalar reconfiguration of state power in favour of regionalization and localization" (Harriss *et al.*, 2004: 2). Today, environmental governance increasingly features multi-partnerships representing more hybrid forms of governance across governments, markets, and communities (Agrawal and Lemos, 2007; Andonova *et al.*, 2009), characterized by new mechanisms, institutions, and types of actors (Auer, 2000; Biermann and Pattberg, 2008). In water governance this approach is reflected by more innovative mixes of local, regional, national and supranational bodies that incorporate both the public and private sectors as part of management regimes (Feitelson, 2000). Some argue that these diverse trends have resulted in a "more fuzzy, Mobius web-like system" that may be more flexible and adaptive but is also less subject to control and less predictable (Gupta, 2011:8). In the process, certain conceptions of what good groundwater governance entails have emerged in both the disciplinary literature and in practice, as we outline below.

5.1 Political and institutional principles

Groundwater governance often includes community involvement, which enables some degree of self-governance along with more formal, instrumental approaches that emphasize laws, regulations, and pricing schemes requiring more government involvement (Schlager, 2007; Giordano and Villholth, 2007: 3). The institutions, or "rules of the game" (North, 1990) within which stakeholders act define the instruments, processes, and organizational context of governance (Kemper, 2007).

However, diverse political and institutional obstacles constrain sustainable water management including "sector fragmentation, poverty, corruption, stagnated budgets, declining levels of development assistance and investment in the water sector, inadequate institutions and limited stakeholder participation" (UNESCO, 2006). The OECD has also pointed out major water governance "gaps" due to limited capacity at the local level, unclear allocation of roles and responsibilities, paucity of transparency, lack of strategic planning, weak economic regulation, and poorly-drafted legislation (OECD, 2011). Overall, good governance of transboundary aquifers can be pursued by establishing the appropriate scales of interest-articulation and decision-making, and involving an assortment of non-state actors as well as formal state agencies (Linton and Brooks, 2011).

Accountability and representation are the cornerstones of good governance; accountability entails legislative, legal, and social responsibilities, as well as remedies. Critical features are the primacy of the rule of law, maintained through an impartial and effective legal system with the ability to implement legal accountability; a high degree of transparency and accountability in public and corporate processes; and a participatory approach to service delivery to assure effective public services. Good water governance also relies upon a viable, strong and well-informed, pluralistic civil society. Institutional pluralism involves the development of a partnership between civil society and government based on dialogue, consultation and collaboration and promoting dialogue, consultation and networking within civil society. In addition, good governance entails sets of rules that enable the institution to perform its role efficiently and effectively.

Some call attention to additional institutional aspects of groundwater management, such as the need for consistent policies, legislation and legal frameworks, strategic management planning, and resource administration capacity (Foster and Loucks, 2006; Pandey *et al.*, 2011; Puri *et al.*, 2001). Increasingly, the institutional and political aspects of governance also include active public participation and stakeholder involvement to help ensure greater accountability (Kemper, 2007:167; Foster and Loucks, 2006; Engle and Lemos, 2010; Pandey *et al.*, 2011; Gleeson *et al.*, 2011; Taylor *et al.*, 2010; Eckstein and Eckstein, 2005; Nowlan and Bakker, 2010). Participation of the stakeholders demands good, symmetric, transparent and reliable information to facilitate cooperation (Llamas, 2004; Llamas and Martínez-Cortina, 2009; Giordano and Villholth 2007; Megdal and Scott, 2011; Puri *et al.*, 2001: 21; Mukherji and Shah, 2005). Learning, sharing, and co-producing knowledge is a key aspect of governance (Engle and Lemos, 2010; Gerlak, 2007; Megdal and Scott, 2011; Cash *et al.*, 2006; Pandey *et al.*, 2011; Hoff, 2009; Ostrom, 2011; Wilder *et al.*, 2010; Pahl-Wostl, 2009). So too are monitoring (Foster and Loucks, 2006; Pandey *et al.*, 2011; Taylor *et al*., 2010; Ostrom, 1990, 2002) and conflict resolution mechanisms (Ostrom, 1990, 2002; Theesfeld, 2008, 2010; Wolf, 2007; Peña and Solanes, 2003) deemed important institutional elements or groundwater governance.

Good governance also calls for a close match between the scale of ecological processes and the institutions that govern groundwater resources (Cumming *et al*., 2006). Problems of biophysical fit can result in non-compliance with groundwater governance (Cohen and Bakker, 2010). Given the broader trends in environmental and water governance toward multi-partnerships and hybrid approaches, it is also important to build capacity across the multiple and diverse governance scales (Kerr, 2007). In addition, interplay between both formal and informal institutions, and across and within scales is seen as important institutional and political elements of governance (Lebel *et al*., 2005; Young, 2002). In particular, the degree of centralization or decentralization of governance will shape on-the-ground outcomes (or groundwater governance outcomes).

Increasingly, resiliency research has emphasized the need for institutional capacity to adapt to uncertainty and change in order to be resilient within a social-ecological system (Folke *et al*., 2005; Gallopin, 2006; Young, 2002; Dietz *et al*., 2003). For water governance, this might mean flexible governance mechanisms that can help stakeholders to anticipate and adapt to various uncertainties and changing circumstances (Drieschova *et al*., 2008; Drieschova *et al.*, 2011; Drieschova and Fischhendler 2010; Wolf, 2007; Batchelor, 2007; Pahl-Wostl, 2007; Pahl-Wostl *et al*., 2008; Huntjens *et al.*, 2010). In the realm of groundwater governance, institutional adaptation and flexibility have been gaining greater attention (Knueppe, 2011; Clifton *et al.*, 2010; Ross and Martínez-Santos, 2010). More adaptive approaches also are likely to better integrate community and instrumental groundwater governance approaches (Giordano and Villholth, 2007: 3).

5.2 Socio-cultural considerations including historical evolution

The concept and existence of water have affected socio-cultural beliefs, norms, and values throughout history. Many of the world's religions hold a special place for water, viewing it as a source of spiritual purification. Hinduism, one of the oldest continuously-practiced religions, assigns a powerful cleansing power to water. Hindus believe that all water is sacred, with rivers, namely most notably the Ganges, having special significance. In Buddhism, another venerable religion, water is used in funerals and offered to attending monks and the corpse. The Judeo-Christian tradition also features water prominently. The Torah, the guiding text Judaism, prescribes ritual washing to maintain a state of ritual purity. Similarly, Christians are dipped in water three times during a baptism ceremony to signify their connection to Christ. And the Sharia or Islamic law includes provisions on water management that require social sharing of water's benefits and burdens (Tvedt and Oestigaard, 2009).

An understanding of groundwater systems — though limited, especially in eras with much less means to assess and study groundwater systems — also shaped mythical perceptions on groundwater. The use of phrases considering groundwater (and freshwater in general) as being gifts of God or of Mother Nature are verbal examples of such perceptions. For a long time even up to the present, many people assume that groundwater is held in underground seas and/or rivers. Until the 17th century, the prevailing belief was that groundwater would move in a direction opposite to what we know now, thus from the bottom of the sea to the mountains through mysterious underground channels, from where springs would emerge (Margat, 2008).

As a necessity, water relates to daily life in many ways beyond the religious and spiritual. As the world population has grown, more attention has been given to the water sources essential for human life. In 2010 two respected publications widely read by general audiences—*National Geographic* and *The Economist*—published special issues on water to bring attention to the challenges associated with meeting increasing worldwide demands for water (*National Geographic*, 2010; *The Economist*, 2010). Groundwater was not overlooked. That large, developing-world cities, such as Dhaka, Beijing, Tripoli, and Katmandu, rely exclusively on groundwater was noted, as was the significant decline in groundwater tables in many parts of the world. Concerns about lack of access to clean water and sanitation and the changes in diets associated with rising income levels, along with associated differences in embedded water, were discussed.

As water demands increase relative to supplies, leading to increased reliance on groundwater, there will be a greater focus on groundwater governance. The explicit integration of socio-cultural principles into groundwater governance can result in the development and implementation of effective policies. These policies can yield a set of practices for 'responsible groundwater use' including equity, sustainability, and efficiency considerations.

Scholars of water-resources management argue that a major paradigm shift in management is underway, from a historically strong emphasis on engineering and technical solutions to a focus on integrated management that also highlights the importance of culture and social learning (Pahl-Wostl *et al.*, 2008a). The Global Water Partnership (2000) emphasizes that effective governance based on principles of equity, efficiency, and diverse knowledge integration is as important for dealing with water resource management problems as technical solutions. Recent literature and evidence-based analysis on water governance also shows that technical, institutional, and financial solutions to the so-called "water crisis" often may be known. The implementation and adaptation of these solutions on the ground to develop place-based policy responses remains challenging (OECD, 2011). Groundwater governance is intimately linked to the development and implementation of norms and principles that promote change in the behaviour of actors across each scale at which groundwater is managed (Pahl-Wostl *et al*. 2008b). Contemporary focus on finding transitional governance approaches to help society move from current unsustainable governance paradigms to future governance paradigms that are more sustainable, hinge on the strong interdependencies and synergies between formal and informal institutions that are embedded in their cultures (Pahl-Wostl *et al*., 2008a; Pahl-Wostl *et al.*, 2008b). Institutions — the formal and informal rules that provide the framework for the behaviour of human beings — include codified laws and regulations as well as the socially-shared rules and norms that develop through social interaction and shared learning (Pahl-Wostl *et al.*, 2007).

Socio-cultural principles are deeply lodged within governance — even if until recently they have remained largely ignored in the dominant management literature — as 'good' governance relates to a regulatory system that shows qualities of accountability, transparency, legitimacy, public participation, justice, efficiency, the rule of law, and an absence of corruption (Pahl-Wostl *et al.*, 2008b). Hassan (2004) introduces the notion of an 'integrative ethic of water management' that supports the cooperation of different users, policymakers, financial agencies, and professionals to exchange information and to achieve trust while promoting accountability and transparency. The need for difficult choices to be made regarding rates of water consumption, wasteful practices, and recycling stresses the importance of considering the role of culture in groundwater management.

The role of culture in governance has recently risen to an important focus of study. This follows the recognition that culture is critical to understanding barriers to changing practices and the adoption of technologies and new management strategies, and to successfully exchanging experiences between developed and developing countries (Pahl-Wostl *et al.*, 2008a). The concept of social learning — a learning process that requires collective action and conflict resolution, and which requires people to learn about their interdependences and differences and to deal with them constructively — is emerging as key to effective water management. The integration of social learning into governance implies a major shift to a style of governance based on collaboration, adaptation, and ongoing learning in a complex and always changing world (Folke *et al.,* 2005; Pahl-Wostl *et al.*, 2007; Pahl-Wostl *et al.*, 2008a; Wilder *et al.,* 2010).

A very important aspect of governance is the idea of social inclusion. As water is absolutely essential for human survival, deliberate exclusion of people from access to it is universally considered as inhuman and *in extremis*, even a crime. Social inclusion in governance also means that policies are developed such that they include evaluation of interests of all groups within a society and that all groups are treated with a same level of fairness. A special case of social inclusion is gender mainstreaming, which has been propagated since the conceptualization of IWRM and which has improved the access and control of women over water resources in many areas. Another dimension of social inclusion is to target marginalized groups like people below a certain poverty level. Lifeline drinking-water tariffs (often even free of any charge) and preferred allocation of scarce groundwater resources to the vulnerable during emergency situations are examples of such policy targeting.

Historically, public policy on water has tended to focus primarily on only one level: local, basin-scale, national, or global. In recent years, however, water has been subject to the globalization phenomenon that has characterized politics and economics (Varady *et al.* 2008; 2009). Going even further, recognition is growing of multi-scale, polycentric governance models that appreciate that a large number of stakeholders in different institutional settings contribute to the overall management of a resource (Pahl-Wostl *et al.*, 2007). Thus multi-level governance based on partnerships across scales represents a more hybrid form of governance that integrates government agencies and diverse stakeholders (Pahl-Wostl *et al.*, 2008b). The OECD defines multi-level governance as the explicit or implicit sharing of policy-making authority, responsibility, development and implementation at different administrative and territorial levels. Evidence from the implementation of the OECD Multi-level Governance Framework "Mind the Gap – Bridge the Gap" in 17 OECD countries and 13 Latin American

Countries suggests that all face common coordination and capacity gaps when designing and implementing water policy, regardless of their institutional setting (unitary, federal) and water challenges (scarcity or not). Regarding issues related to groundwater governance, these gaps are of several types, including administrative, information, policy, capacity, funding, objectives, and accountability gaps (OECD, 2011).

The need for collaboration is crucial at this point in time because interdependence between government bodies and stakeholders is increasing as government budgets decrease and the efficacy of traditional command-and-control management is reduced. Furthermore, Pahl-Wostl *et al.* (2007) contend that the combination of top-down and bottom-up formation of institutional arrangement may in fact lead to greater acceptance across the wide range of stakeholders involved in the governance process. Recognizing the need for adaptive co-management of complex social-ecological systems, such as groundwater, Folke *et al.* (2005) emphasize integrating dynamic social learning opportunities within a cooperative management framework; they also stress the importance of networks, leadership, diversity, and trust for accumulating experiences and collective memory that can be used to effectively cope with surprise and disturbance, such as drought.

Challenges remain in terms of effectively integrating socio-cultural principles, including equity, culture, social learning, and cooperation into existing groundwater governance regimes. In considering any arrangements that impact the interests of individuals and communities in regard to their use of water resources, The Food and Agriculture Organization of the United Nations (FAO, 2011) identifies three core principles that should be considered: security, sustainability, and equity. However, balancing the three principles is a key challenge for policy- and decision-makers as concerns for security tend to outweigh considerations of sustainability and equity. Water resources play a crucial role in terms of basic needs and livelihoods and thus gender and social equity factors must be taken into account in policy-making. Thus, hard decisions about water resource allocation (and increasingly more frequently, re-allocation) under conditions of water scarcity must be perceived as fair by all stakeholders and water users involved (FAO, 2011).

Institutional and cultural arrangements further complicate water management decisions as holders of water rights under informal, customary arrangements may reject becoming involved in formal water tenure arrangements. In the 1980s, for example, Douglas Merrey and his associates were recognizing the critical role of *izzat* (Islamic honour) in decision-making for irrigation systems in Pakistan and northern India (Merrey and Wolf, 1986). And a recent case study from Bukhara, Uzbekistan, highlights how water governance is affected by socio-cultural considerations, such as underlying traditions and ethics of water use. In Bukhara, the historic role of water magistrates illustrates how sharing water has been organized, both institutionally and ethically, in many regions. Although an oasis in a water-short region, Bukhara became a brilliant metropolis because of an elaborate irrigation system used by the population for daily social exchanges. Bukhara is a good example of the importance of social organization in water management, in this case via irrigation (Fried, 2008).

5.3 Economic principles

Economics is concerned about the allocation of scarce resources. Microeconomic principles tell us that the price of a good or commodity should relate to supply and demand. The supply or availability of a good for consumption will depend on the costs of production. The demand will depend on the willingness and ability to pay for the good. In an ideal or typical setting, the price signals associated with markets will equilibrate supply and demand and result in an efficient allocation of resources, whereby goods are distributed to their highest valued uses.

Water, however, is not a typical economic good (Ostrom, 2002). From a societal perspective, it is necessary for life. All require some access to water for basic existence, yet ability to pay for water depends on the purchaser's income or financial resources. Physical access to groundwater requires the ability to extract the resource, but, absent restrictions, one person's access does not prevent another from tapping into the same aquifer. Rather than seeing water exchanged through a typical market mechanism, wherein multiple buyers and sellers act as economic agents, water is often distributed to customers in a community by a monopoly provider. It may be distributed to agricultural users through a cooperative irrigation association. Alternatively, groundwater users may own and operate their own extraction wells. For many, groundwater may not be the only source of water and its use may or may not be subject to regulation.

Pricing or price signals can assist in the allocation of all types of water, not only groundwater. However, where markets are nonexistent or imperfect, pricing may not accurately reflect the costs and benefits of supplying and consuming the good. Measuring the economic benefits or value of groundwater is important to sustainable management of its quality and quantity but is difficult to accomplish (EPA, 1995; GW-MATE Briefing Note Series Note 7, 2004; Gorlach and Interwies, 2003). Understanding all the costs associated with water provision is likewise important but challenging (Mukherji and Shah, 2005). Significantly, around the world water prices rarely reflect full the costs of water provision, and do not typically assign any cost of the water molecules themselves (Megdal, 2005).

As water demand has increased relative to supply and water sources have become polluted, recognizing the scarcity of this essential resource is important. Measuring fully the economic implications of groundwater provision is difficult due to the absence of key data (Koundouri, 2004a, 2004b). The quantity of groundwater in storage, which depends on groundwater recharge as well as extraction rates, often is not known. The water quality impacts of contaminant intrusion are difficult to measure. Groundwater use itself often is not measured, making it impossible to connect economic payment with utilization. Where water is priced, water prices incorporate the known and measurable costs of water provision, such as construction, operation, maintenance and administration of the water extraction and distribution system. Yet, these costs may not fully reflect the costs of water extraction, such as instances where electricity rates are subsidized for certain users (Mukherji and Shah, 2005). Water prices rarely include consideration of the third party and environmental impacts of groundwater use (Foster, 2006). For example, water extracted by one user can result in higher pumping costs to the nearby well owner. Those pumping groundwater rarely have to pay the costs of environmental degradation due to declining water levels. And while water pricing should assist in allocating water to highest valued uses, the ability to pay is, of course, a critical consideration. Water that is needed for essential functions, such as cooking and cleaning, should be affordable. Indeed, in places where water is metered and priced, regulatory policies often take into account such considerations.

Water in cities and towns is often sold by monopoly providers, resulting in the customer having only one supplier available. Without regulatory oversight, the monopoly provider could take advantage of its single-seller position and charge high prices for water. Hence, there is the need for some process for overseeing and setting water rates, whether the water provider ownership is public or private (Megdal, 2012). The actual and potential roles for the private sector in water provisions are multi-faceted and a topic of debate (Morrison and Gleick, 2004). As access to capital becomes more important to provision of clean, reliable water services, the role of the private sector and public-private partnerships is likely to grow.

As the competition for water increases, many are interested in facilitating more trading opportunities for water. Market-type mechanisms are seen as having the potential to match demand with available supplies. (For a sampling of analyses, see Garrido, 2011; Thompson *et al*., 2009; Plagmann and Raffensperger, 2007; Raffensperger *et al.*, forthcoming; Zhang *et al*., 2008; Zetland, 2011). Water transactions depend on the seller of the water possessing the right to in fact engage in the transaction (Hildering, 2004, legal paper that is part of this effort).

Economic considerations are fundamental to other policy options, such as groundwater extraction levies and conservation programs. Although difficulties abound, more attention to identification and measurement of economic factors influencing supply and demand, as well as the economic analysis of alternative policies, will be important to effective groundwater governance.

5.4 Ecological principles

Physical characteristics of groundwater systems partly determine consequences of human use. This necessitates the application of ecological principles in order to manage groundwater resources sustainably.

In many parts of the world, groundwater resources are ubiquitously available in large volumes of good quality. Developing access to these resources is in such places rather simple and cheap, and often does not entail large governmental coordination or support. Mukherji and Shah (2005) mention that these intrinsic hydrological advantages of groundwater give rise to several scale-neutral socio-economic benefits, making it a favoured grass-roots level source. That groundwater sources tend to be more reliable and predictable than surface water sources often yields significantly higher economic returns per cubic meter of water used for irrigation. This adds to the preference for using groundwater (van der Gun and Lipponen, 2010). As a consequence, in many parts of the world (especially rural areas) groundwater use consists of the accumulation of numerous local groundwater development decisions by individuals, each with distinctive needs and preferences.

In addition, aquifers are conducive and diffusive systems. The first characteristic results in the physical consequence that effects of interventions in the aquifer may propagate through it (even crossing administrative or any other human perceived boundary) while the second characteristic dampens this effect with time and distance to the location of the intervention. Additionally most aquifers are not isolated physical systems but an integral part of hydrological cycle process and indivisibly connected to other water (and land) systems. Groundwater systems are replenished from infiltrating precipitation, infiltrating rivers and lakes and irrigation return flow. On the other hand groundwater discharges in these surface water bodies and in the sea and transpires through groundwater-table dependent vegetation. Hence, effects of interventions in groundwater systems not only propagate through aquifers, but into the linked systems as well and vice versa (Acreman, 2004; Custodio, 2002). A result is that humans, by interfering with these systems (e.g. by groundwater pumping), may affect other locations. In turn, this can disrupt others users' ability to employ the groundwater system, thus causing so-called externalities. This insight has led to more holistic management and recognition that the scale of management should fit the scale of the physical systems. The insight also prompted the cause-no-significant-harm principle (*sic utero tuo ut alienum non laedas*), i.e. "use your own groundwater resources without harming that of another."

In some cases, groundwater is a renewable resource. As the aquifer is connected to surface water systems and to the land surface, it has the ability to be replenished with passage of time. This renewability is depending on the level of connectedness with these systems and with the availability of water in these systems such as filled rivers and excess precipitation (Foster and Loucks, 2006). Groundwater resources in aquifers without this connectedness and replenishment, or in aquifers where the rate of abstraction exceeds the rate of replenishment, are assumed to be non-renewable and get mined. Mining of such natural resources appears to violate the narrow physical definition of sustainability, which is usually interpreted by hydrogeologists and groundwater resources managers as the ability to continue pumping without aquifer exhaustion. Such practices may, however, be justifiable from a broader definition of sustainability that reconciles the use of the non-renewable resource with "sustainability of human life" (van der Gun and Lipponen, 2010). In this case, so-called non-sustainable groundwater use may be necessary to sustain livelihood options or even immediate human survival when no other water source is present.

A salient question is how to save groundwater resources for future generations. Groundwater mining requires a successful exit strategy, implying that by the time the groundwater resource is substantially depleted, society will have used it to advance economically, socially, and technically so as to enable future generations to develop substitute water sources at an affordable cost. Additionally, it is important to know how to deal with the environmental sustainability of ecosystems that are groundwater-dependent. The bottom line is that sustainability has many dimensions and interpretations, and that decision-making to achieve sustainability often includes tradeoffs between these different notions. As the level of connectedness and hence renewability is often strongly dependent on aquifer depth, different types of governance including sustainability considerations are suggested for different depths of the aquifer (López-Gunn and Jarvis, 2009).

As groundwater systems are often linked to and nested within other physical systems with various feedback mechanisms at different scales since aquifers often contain high level of heterogeneity and anisotropy, its system behaviour is only predictable to a limited extent. Furthermore because of its subsurface nature and the inherent difficulty of monitoring groundwater systems are characterized by inadequate information or so-called epistemic uncertainty (Millman and Ray, 2011). Often even the boundaries of the systems remain fuzzy (Theesfeld, 2010). Because of the vastness of the systems, negative consequences of aquifer overexploitation and contamination appear after a certain time lag (Theesfeld, 2010). The impact of excessive withdrawals, for example, can initially be largely invisible (Linton and Brooks, 2011). The open access nature of the vast groundwater systems, allows groundwater use to be distributed and to consist of large numbers of independent of sometimes even unknown groundwater users (Linton and Brooks, 2011).

With climate and global change, groundwater balances in many areas will change bringing in another level of uncertainty (Green *et al*., 2011). Hence groundwater systems could be defined as complex adaptive systems characterized by self-organization, adaptation, heterogeneity across scales and distributed control (Pahl-Wostl, 2007). As relevant data on the status of the aquifer are commonly limited, as many abstractors are involved and as impacts are not easily detected and commonly emerge with a delay, there are substantial uncertainties and risks that have to be taken into account in managing non-renewable groundwater resources (van der Gun and Lipponen, 2010). These characteristics require the application of risk-based and adaptive approaches to be able with constant changing conditions and unexpected consequences.

While aquifers are much less vulnerable to anthropogenic pollution than surface water bodies, when aquifers become polluted, contamination is persistent and difficult to remediate as a result of their large storage, long residence times and physical inaccessibility (Foster, 2006). Some aquifers hold a natural attenuation capacity and are able to partially degrade contamination substance. However some of the derivatives of such processes may be equally toxic and/or mobile as the original pesticide compounds themselves (Foster and Chilton, 2003). This irreversible characteristic of aquifer systems plus the limited ability to predict its system behaviour justify the use of the precautionary principle which generally implies that there is a social responsibility to protect the public from exposure to harm, when scientific investigation has found a plausible risk. Only after further research findings proof that no harm will occur, protective measures can be relaxed.

Because of the vastness of the characteristics of groundwater systems it is costly and (but not impossible) to monitor groundwater abstraction (and even more difficult groundwater pollution) and to exclude potentially new groundwater appropriators or polluters. Combined with the above-mentioned physical characteristics of diffusivity, conduciveness, slow attenuation rates and sometimes limited renewability, additional groundwater development and land use may rival existing uses. These combined features put groundwater system in the category of common property resources which makes them vulnerable to over-exploitation and/or under-management (Ostrom, 1990).

Generally, humans put a high value on groundwater resources as they get abstracted and consumed or used as a production factor in agriculture or industrial activities. The aquifer is hence traditionally valued because of its provision service. However, the systems-based approach in research led to the understanding that groundwater often plays an important role to sustain marine, aquatic and terrestrial ecosystems on which humans depend (Bergkamp and Mackay, 2007). Hence increasingly, the notion of the importance to reserve some groundwater for nature plays part in groundwater management decisions. This eco-system approach broadens the notion of sustainability. Van der Gun and Lipponen (2011) argue that the key question then is not whether the development of a particular groundwater system is sustainable, but rather whether the complex of natural resources (to which that groundwater system belongs) allows and supports sustainable socio-economic development and preservation of desired environmental conditions in the region.

5.5 Approaches by institutions to apply principles

United Nations Development Program (UNDP): In 1997, UNDP adopted good governance principles that emphasize participation, rule of law, transparency, responsiveness, consensus orientation, equity, effectiveness and efficiency, accountability, and strategic vision (UNDP, 1997). For the UNDP, governance can no longer be a closed system and includes the state, but transcends it by taking in the private sector and civil society. The state creates a conducive political and legal environment. The private sector generates jobs and income. And civil society facilitates political and social interaction - mobilizing groups to participate in economic, social and political activities. The state's task is to find a balance between taking advantage of globalization and providing a secure and stable social and economic domestic environment.

Importantly, these principles reflect broader principles discussed above and reflect an evolution in the nature of the approaches adopted as well as the scope of actors involved in water governance. Following on UNDP principles, a number of other organizations in the past decade have adopted similar good governance approaches, including the Global Water Partnership (GWP) (Rogers and Hall, 2003) and UNESCO (2009).

IWRM: Advanced by the Global Water Partnership (GWP), integrated water resource management (IWRM) is an important element of water governance that has emerged in the past two decades. IWRM is a process that promotes coordinated development of water, land and related resources to best maximize social and economic welfare without compromising the sustainability of vital ecosystems (GWP, 2000). It is seen as an alternative to top-down, sector-by-sector management and serves to promote many of the governance principles outlined above. IWRM calls for physical, sectoral, and organizational integration (Kidd and Shaw, 2007), which may result in new institutional arrangements to provide formal coordination in decision-making for water allocation and management (Bressers and Kuks, 2004). Central to the implementation of any institutional development is the presence of sufficient human and institutional capacity (Jaspers, 2003). There are four important principles of IWRM:

1) Water as a finite and vulnerable resource: In the context of groundwater, this calls attention to the vulnerability and limits to the resource (Foster and Skinner, 1995; Foster et al., 2005, Vrba and Zaporozec (eds), 1994).
2) Participatory approach: Stakeholder involvement in planning and management decisions is an essential element to IWRM (GWP, 2004). Bringing in more diverse stakeholders make help to make water management decision-making more equitable (UNEP, 2006; GWP, 2007). It may also help to support adaptation and learning, and help management systems respond better to uncertainties and change (Folke *et al*., 2005; Pahl-Wostl, 2007).
3) The important role of women: This includes the involvement of women as an ethical value (Aureli and Brelet, 2004) and calls attention to gender awareness and rural women as water users (Asmaal, 2004).
4) Water as an economic good: This is in line with the Dublin Principles (1992) and represents greater attention to economic efficiency in water governance. For groundwater, the economic value of water is seen as important in making allocation decisions between competing and different water sectors, and helping to guide decision-makers in the prioritization of investment (Taylor *et al.* 2010: 60).

Millennium Ecosystem Assessment: On June 5th, 2001, Kofi Annan, Secretary General of the United Nations, launched the Millennium Ecosystem Assessment (MA), an international initiative to respond to the ailing environmental conditions of the globe (Tawfik *et al.*, 2009). The main goal is to draw public decision-makers' attention to the necessity to protect the environment in order to maintain economic activity as well as human well-being**.** It is designed to meet the needs of decision-makers and the public for scientific information concerning the consequences of changes on human well-being and options for responding to those changes. The MA is a multi-scale assessment consisting of interlinked assessments undertaken at local, national, regional and international levels.

The MA introduced a new framework for analyzing social-ecological systems that has had wide influence in policy and scientific communities. The MA used a new conceptual framework for documenting, analyzing, and understanding the effects of environmental change on ecosystems and human well-being. It viewed ecosystems through the lens of the services that they provide to society, how these services in turn benefit humanity, and how human actions alter ecosystems and the services they provide (Daily and Matson, 2008). The MA utilizes a broad definition of 'ecosystem services' (Millennium Ecosystem Assessment., 2005):

- Provisioning services like food, *freshwater* and fiber
- Regulating services like climate and flood regulation
- Supporting services like soil formation and nutrient cycling
- Cultural services like spirituality, aesthetics, education and recreation

Freshwater is fundamental to life and contributes to all the major benefits provided to people, both directly and indirectly, from ecosystems. Freshwater ecosystems include groundwater systems along with permanent and seasonal surface and geothermal sources.

PART 2: DIAGNOSIS

6. Assessment of Governance, Policy and Management Practices – What have we found?

Part 2 provides a descriptive diagnosis of groundwater governance based on what has been published in academic literature. At this stage no normative framework was used to perform the diagnosis. Instead, a more narrative discourse on groundwater governance is assumed to be a more appropriate tool to reach the objectives of this project.

Moreover, this diagnosis is based solely on papers and scientific work that directly address the issue of groundwater governance. This topic is truly innovative and, as such, few papers have yet been produced on it. Therefore, this diagnosis covers a wide array of papers and studies on the diverse subjects of groundwater, surface water, and more general natural resource management, as well as papers applying theoretical approaches to the subject of natural resources governance and policy-making.

The case studies described below demonstrate a great diversity of settings and governance issues. Case studies are drawn from developed and transitional countries, with different climates and stages of socio-economic development, and exhibiting variation in the level of groundwater dependency. The case studies were chosen to present a wide and varied look at diverse governance issues such as participation, the subsidiarity principle, use of diagnostic tools, data and information, the role of global or bridging organizations, the role of scale, market mechanisms, and many others. The well-studied case of the Arizona aquifer is described in somewhat greater detail than the others and is also included as an example of an aquifer's ecosystem services.

In the sections of Part 2 we highlight some illustrative case studies to better describe the scope of groundwater governance around the world today. Based on our review of the broader case study literature, we outline next a set of barriers and opportunities. We conclude with an overview of the evolution of successful and unsuccessful paradigms, models, instruments, methodologies with respect to groundwater governance.

7. Lessons learned from Illustrative Case Studies

7.1 Domestic and transboundary case studies

Some studies of groundwater management in South Asia call attention to self-regulation as a governance model (Shah, 2000; van Steenbergen and Shah, 2003, 12 in Llamas and Custodio). For example, in Saurashstra in the State of Gujarat, India, when government efforts failed to adequately address the over-exploitation of groundwater and subsequent declines and coastal groundwater salinization, some local community members began to harvest excess rainwater during the monsoon for aquifer recharge. Based on informal rules, and inspired by a local spiritual Hindu leader, the grassroots movement grew fast. The early adopters acted as change nucleus, inspiring neighbouring farmers in nearby villages, and operating as an open and inclusive network. Although the initial focus was on increasing water supply, some demand-side practices were adopted as well. The social cohesion in the villages and in the religion helped to ensure greater compliance. The movement received public recognition from the Government of Gujarat (GoG) resulting in a pluralistic co-existence of formal governmental groundwater legislation and informal movement norms and rules. Technical backstopping from the GoG and locally working NGOs also served to improve effectiveness. Financial support from merchants of a nearby diamond industry originating from these rural areas gave another boost. This case can be seen as a public-private partnership '*avant la lettre*' with cooperation between governmental departments, citizens, communities, religious-based community based organizations, NGOs and the private sector.

Groundwater management strategies in India can be contrasted with those in China (Mukherji and Shah, 2005). Since the 1950s, both countries, facing high population density and embracing food self-sufficiency and an agriculture-based economy, have relied on groundwater irrigation for their immense agricultural productions (Siebert et al., 2010). This has led to overexploitation with consequent groundwater-table declines in large parts of their territories. In some instances groundwater markets have emerged to allocate groundwater to those without functioning wells. Generally, despite the existence of IWRM plans and groundwater legislation in India today, there is poor governmental implementation and enforcement. A recent World Bank study (Garduño *et al*, 2011) concludes that the weakest element in the Indian groundwater governance chain is the institutional capacity at central and state levels. The study adds urban groundwater and groundwater contamination as urgent issues. In contrast, China's groundwater management has been much more centralized and successful in implementation and enforcement. Each Chinese village features a governmental agent paid from villager's taxes with the responsibility to plan and manage its irrigation. Such officials provide guidance for price setting mechanisms in groundwater markets. Differences between the Indian and the Chinese experience suggest the roles that both the macro-development path (Shah, 2007) as well as the overarching political regime play in the shape and scope of the groundwater governance. It also shows challenges associated with IWRM in areas of the world where the rate of institutional capacity adaptation lags behind social change.

Further west, in Spain, we can come to understand how past practices and policies influence and constrain present groundwater governance (Llamas and Garrido, 2007).Traditionally, with a strong governmental bias towards surface water infrastructure, Spain has one of the highest number of surface reservoirs per capita and large volume of interbasin river water transfers. This is in large part due to past failures associated with groundwater dependence for public water supplies (i.e. 19th century groundwater-fed khanat system failure to provide water to Madrid). As a result, groundwater has been part of a stereotyping hydromyth assuming that groundwater use always lead to the depletion of the source making it unreliable. Groundwater came to be used largely in rural areas where farmers were not served by surface water systems. Considered to be private property attached to land endowments, the landowner could pump as much as he wanted unless a third person was affected. However, intensive groundwater use (partly promoted by the government in the '50 and '60s) led to a hazardous situation. The Spanish Water Code of 1985 turned groundwater resources under the public domain. For the already existing groundwater users usufruct rights were automatically granted based on the rate they had historically be using but under the condition of getting registered. Every new groundwater abstraction would require a permit by the corresponding water authority. Yet, many Spanish groundwater abstractions go unregistered today. In part this is because the government lacks the capacity and resources to carry out the enforcement. But it is also because of the historic notion of groundwater as private property, which hinders registration and licensure. The 2001 National Water Plan appears to challenge the old paradigm of surface water infrastructure development. For the first time, it has a provision that strongly supports the management of groundwater resources. It states that no Ebro River water can be transferred to any overexploited aquifer before intensive groundwater research has been carried out and alternatives thoroughly evaluated. Furthermore, it fosters the formation of groundwater user communities and educating the general public on groundwater.

A case of climate change adaptation and groundwater governance in East Anglia in the UK reflects implementation of IWRM principles and connections to the larger regional European Union Water Framework Directive. As one of England's most productive agricultural areas, farmers and food processing industries depend on groundwater irrigation and groundwater for drinking water supply. Groundwater resources are managed by the Environmental Agency (EA, an executive non-departmental Public Body responsible to the English Secretary of State for Environment, Food and Rural Affairs) through a first-come first-served licensing process (most recently with a 12-year validity) and with a drought allocation prioritization of drinking water first, then environment and irrigation. Although it is difficult to comprehend why the EA would initiate climate change adaptation processes when most picture an often green (and wet) England, the stark reality is that currently the available groundwater is completely allocated, mostly to the politically powerful groundwater-dependent farming/food processing sector. Future droughts and groundwater loss would mean huge economic losses for the region. As a result, the EA initiated Water Abstractor Organizations providing local groundwater stakeholders participation in policy and policymaking. In a participatory fashion, the following adaptive measures were developed: reduction of licenses' time-limit to 6 years, changes in land practices to reduce groundwater contamination, more efficient irrigation techniques and on-farm winter water harvesting. This case demonstrates how an IWRM-based approach increasingly took environmental needs into account and how the regulatory authority used public participation as an instrument to further improve its IWRM-capacity.

In Africa, the countries which share the North Western Saharan Aquifer System (NWSAS), recently agreed to begin an incremental process toward joint management under the supervision of the Observatoire du Sahara et du Sahel (OSS). Shared by Algeria, Tunisia and Libya, exploitation of the aquifer has occurred faster than it gets replenished in this arid area. Hence this aquifer system is non-renewable and with the current abstraction rates the groundwater resources are mined. This has meant negative consequences for these countries internally and represents potential risk of conflict across states. The first step has been a joint technical fact-finding study with sharing of the countries' data in a central database maintained by OSS. With technical backstopping of OSS, a numerical groundwater flow model was built and the effects of agreed future use scenarios were calculated. While this was mainly a technical exercise, OSS and the UNESCO-IHP and IAH Internationally Shared Aquifers Resources Management Program continued to raise awareness on the necessity to manage these resources at policy-making and political level and it was agreed to start a consultation and dialogue mechanism to keep each other informed. This case suggests the importance of an incremental approach towards more cooperation and the use of a neutral bridging organization (OSS) in the case of a transboundary aquifer. It also reveals the role of agreed data and models to base further dialogue on factual information and using ISARM as a Community of Practice to share their learning with and learn from other similar areas in the world.

Groundwater management in South Africa illustrates the role of legal and institutional change and decentralization in governance (Knüppe, 2011). Since its democratization in 1994, South Africa has undergone fast socio-political changes, including reform of its water law. The National Water Act (NWA) of 1998 provides for basic access to water and calls for management of water resources based on principles of equity, efficiency and sustainability. One important instrument in this law is the so-called Ecological Reserve stating that before any abstracted water is allocated for human use, the environmental requirements of the particular resource where the water is taken from should be determined and reserved. The National Water Resource Strategy and the Guidelines for Groundwater Resources Management provided the methodological and scientific basis for the NWA and is strongly based on the IWRM-approach. The process is decentralized with the Department of Water Affairs (DWA) exercising overall responsibility and regional offices in nineteen water management areas and catchment management agencies at the more local scale. The formulation of water users associations guarantees participation from users at grass-root level.

The changes have been deemed to be only partially successful. According to local experts, there are several reasons for this. First, groundwater sources are relatively undervalued by both average citizens who consider it to be a poor man's source, and by water engineers and policy makers who have historically worked with large-scale surface water structures. Second, human expertise to deal with groundwater resources is lacking across all management levels and reflects a relative absence of hydrogeological and socio-economic data to make informed decisions. Provisions to control groundwater abstraction and pollution are weak or even non-existent at more local levels (Pietersen *et al.*, 2011) so are provisions for the establishment of aquifer management organizations. Third, despite the institutional reform, groundwater is still being decided upon fragmentarily in different state departments. Furthermore, the assignment of responsibilities, roles, tasks and resources between the various DWA scales is unclear. This is also confirmed by a recent World Bank study on South African Groundwater Governance, which concludes that at the national level technical, legal and institutional provisions are basically reasonable but weak for cross-sector policy coordination (Pietersen *et al.*, 2011). Bottom-up movements towards public participation are poorly recognized nor enabled by the groundwater managers and governmental agencies. Finally, the ecosystem services of aquifer are rarely recognized despite the existence of the Ecological Reserve. These factors suggest the challenges associated with institutional and legal reform and the realization of equitable, sufficient, and sustainable groundwater management.

An interesting case study is that of the arid and strongly groundwater-dependent state of Arizona in the U.S. Aside from drinking water quality and discharge standards, which are established at the federal level, the individual states have the discretion to establish their own groundwater rights and management systems (Megdal, 2012). State-wide, groundwater accounts for about 40 percent of total water extractions/diversions (Arizona Water Atlas, accessed 18 December 2011). With its adoption of the 1980 Groundwater Management Act (GMA), Arizona became a national leader in managing groundwater in the areas designated as Active Management Areas (AMAs) (Colby and Jacobs, 2007). These areas were identified statutorily due to extant groundwater mining. Groundwater rights and permitting regulations were established for the major water using sectors – municipal, industrial and agricultural – with each sector having to abide by conservation programs established by the Arizona Department of Water Resources every 10 years. Key to the GMA was the establishment of statutory management goals for each of the AMAs as well as a program of assured water supply, whereby new municipal developments are required to show they have legally, physically and continuously available water supplies for 100 years. Use of groundwater must be consistent with the management goal, which for most of the five AMAs is the attempt to reach safe-yield, meaning long-term withdrawals of groundwater do not exceed natural and artificial recharge. The natural terrain, economies and water resources of the five AMAs differ, and there is some ability to customize regulations in recognition of the differing conditions. A statutory framework for recharge and recovery has allowed water to be banked for future use and groundwater recharge to serve as a treatment mechanism for Colorado River water in lieu of the construction of costly treatment plants.

Arizona's GMA is hailed as a progressive approach to groundwater regulation and has allowed for significant innovation and variation in water user approaches to meeting the state-established regulations (Colby and Jacobs, 2007). However, after 30 years of experience, the water management challenges remain substantial. Even in the large AMA regions, where safe yield is the management goal, there are areas where localized draw-down of water tables is a concern. The assured water supply framework allows for groundwater to be pumped to depths as low as 1,000 feet (303 meters) below land surface, provided most of that groundwater is replenished with surface water supplies. However, the Central Arizona Water Conservation District, the agency responsible for replenishment, does not have long-term renewable water supplies under contract to meet the projected replenishment obligation. Among the related concerns, therefore, is the future cost of replenishment. There are no penalties for non-achievement of the management goals, and many small wells are exempt from regulation. Although about 80 percent of Arizona's approximately 6.5 million people live in an AMA, some of the non-AMA areas of the state are facing projected imbalances in water supply and demand (WRDC, 2011). The difficulties and data gaps associated with quantifying the water needs of water-dependent natural systems (Nadeau and Megdal 2011) and lack of legal recognition of environmental water needs (Megdal *et al.*, 2011) result in lack of policies addressing the water needs of nature . Although the 1980 Groundwater Management Act provided a strong foundation for groundwater management, much work remains. The experiences of Arizona indeed point to the complexities associated with groundwater management in growing, semi-arid regions where groundwater is a crucial part of the water supply.

7.2 Groundwater in emergency situations

One particular issue of groundwater governance relates to groundwater in emergency situations. Emergency situations are defined here as those natural hazard like floods and droughts and man-made hazards like violent conflicts that significantly affect the functioning of societies and hence adversely affect human life. Immediately after physically securing an endangered population, the priority of emergency relief mostly considers drinking water distribution since existing drinking water supply systems are often rendered dysfunctional. Ignorance and professional bias by the relevant authorities and emergency relief NGOs and the lack of information on the presence of high yielding aquifers with safe groundwater limit the ability of the (ad-hoc) emergency sector to include simply exploitable, locally available and non-affected groundwater resources as a relief solution. Instead, complicated emergency water supply systems based on transfers of large volumes of water from elsewhere are often developed.

Under UNESCO International Hydrogeological Programme (VII), a Working Group IHP project on *Groundwater for Emergency Situations (GWES)* was established. The main project outcome are methodological guidelines for the identification, investigation, development, management of strategic groundwater bodies to be used in emergency situations resulting from extreme climatic, hydrological and geological events and in case of conflicts and to formulate principles of groundwater governance policy in emergency situations (Vrba, 2011). Within the GWES project, various project proposals with 'groundwater solutions' have been developed for a number of disaster events in India, State Orissa (flood and storm), Pakistan (flood), Somalia (drought) and Haiti (earthquake) after assessments by teams of local and international groundwater experts.

What is of relevance to governance is that in emergency situations commonly practiced general principles of equity, sustainability and efficiency are hardly valid or get very different meanings. The actors and related economic, social, ecological and scientific/technical activities and the needed policy response for emergency groundwater resources even differ between the different phases of a disaster event (preparedness, warning, impact/relief and rehabilitation). For instance, groundwater abstractions rights may need to be temporally overruled to facilitate the allocation of groundwater resources to drinking water supply. Sustainability policies cannot strictly be adhered to as providing water to safe human life now is more urgent than managing groundwater resources to sustain future human life or to sustain natural systems on which people depend less directly. Of great importance is to include groundwater resources in national disaster risk reduction and preparedness plans and in the emergency relief plans and operations. With climate change, the frequency and intensity of disaster events are expected to increase in many areas of the world. Hence, the relevance of groundwater governance for emergency situations.

7.3 Groundwater use going global

The final case study considers the whole earth and looks at groundwater resources as a global common property resource. Globalization has caused water use impacts to reach global dimensions and countries across the globe are thought to be linked through so-called water teleconnections (Hoff, 2009). As an illustrative example, India's groundwater overexploitation is assumed to have contributed significantly to the recent sea level rise (Konikow, 2011). The main groundwater teleconnection is through the international trade and transport of groundwater-irrigation based food and (increasingly important) bio-fuels. From a global perspective, this virtual water transfer appears to be sustainable as it saves about 300-450 km^3 of water annually as food is grown in areas with relatively high water productivities and imported by countries with low water productivities.

Although land-acquisitions by multi-national companies have been common in recent history, there are increasing concerns related to the large-scale land acquisitions by countries lacking arable land and/or water resources to sustain their national food security. Since 2004, more than 2.5 million hectares have been leased and/or sold in Africa to governments and some companies of the Gulf States, China, Libya, India, and South Korea (Cotula *et al*., 2009). It has been argued by some that water is the hidden agenda behind many of these land acquisition deals (HLPE, 2011). Cases are observed where the intensive agricultural production rates on these land acquisitions have led to negative environmental externalities such as water mining and nutrients loss and making its local sustainability questionable. Additionally, cases are known where governments stopped respecting the non-formalized local and traditional land and water use rights. Several governments (such as Tanzania, Ethiopia, Mozambique, Cambodia) have made efforts to identify 'available' land which is only non-formally entitled to local people through traditional rights and that can be 'allocated' to investors. With climate and global change, about 20% more water than today is needed to meet the food demand in 2025 (Hanjra and Qureshi, 2010) and hence this search for land plus water is not likely to stop. The global groundwater governance community (basically led by human rights community) have only recently started to address these issues of global groundwater governance.

8. Constraints and Barriers

Our review of the diverse case study literature on groundwater management, as well as our analysis of the more illustrative case studies presented above, leads us to identify a set of broad barriers in terms of groundwater governance.

8.1 Inertia and resistance to change

Within some countries, historical access and ownership rules led to a concentration of power and access to resources in the hands of the few — who also had a key role in institutionalizing rules that protected these rights (Gupta and Lebel, 2010). Hence, individuals, organizations and sectors tend to favour the status quo when it is known or perceived that the new institutional constellation is going to provide less benefits (Cumming *et al.*, 2006). Discourses and rules on the management of water resources at the national level are often influenced by practices at the international level, through development cooperation, development banks and international social movements. These aspects of globalization often foster homogenous rules that may face more national or local resistance (Gupta and Lebel, 2010). Finally, the intensive use of groundwater resources is of relatively recent origin, dating back no more than half-century in most countries (Knueppe, 2011). Institutional capacity is lagging behind the technological development and economic and cultural valuation of the natural resource (Cumming *et al.*, 2006).

8.2 Rent-seeking behaviour

In particular governance regimes, groundwater users may form a large part of the electorate. Politicians may fear negative polls as a consequence of trying to implement policies that constrain the perceived groundwater use rights of those users. Populist, electoral motives drive policy-makers to abstain from or delay the implementation of such policies (Mukherji and Shah, 2005). Furthermore, mechanisms of patronage result in the formulation of distorted or perverse policies privileging some elites or sectors and to corruption within governmental organizations (Garduño *et al.*, 2010; Cumming *et al.*, 2006).

8.3 Problems of fit

The time scale of issues in groundwater resources systems often exceeds the standard terms of the responsible governmental administrations. Changes in such administrations after elections often pose a discontinuity in groundwater governance arrangements. Also, despite the promotion of system-based and holistic approaches to water resources management, the boundaries and scales of the governmental entities responsible for the management of groundwater resources generally do not align with the physical boundaries and scale of the system (Cash *et al.*, 2006). As well, in general, key aspects of groundwater resource policy and law were formulated at an earlier time, when encouraging exploration was the main goal (Cumming *et al.*, 2006). Slow re-adjustment of those policies and laws renders them unfit the deal current conditions and issues.

8.4 Problems of interplay

Despite the promotion of system-based and holistic approaches to water resources management, the management of groundwater resources is still fragmented and placed in different functional departments. Some functional departments may perceive sustainability issues as outside of their responsibilities (Sonales and Jouravlev, 2006). Cooperation and coordination across departments and functional units is often lacking. The consequent "Silos" policies and isolated lateral planning lead competing and conflicting preferences and decisions and to sub-optimal solutions (Cumming *et al.*, 2006). In addition, because groundwater governance may include the transfer or devolution of tasks and responsibilities from central (capital based) departments to more local (province or city based) governmental entities, this may induce resistance (Theesfeld, 2010) and further problems of interplay.

8.5 Information deficit

In many countries, groundwater resources management is characterized by continuous information deficits, particularly around monitoring and quality (Foster and Chilton, 2003). When the available information is incomplete or incorrect, it becomes harder to realize the significance of the problem. In other instances, too much information of the wrong kind is collected; data gathering and analysis can then become traps that distract members of the organization from truly coming to grips with the key issues (Cumming et al 2006). While technical data and information on groundwater resources are often poor, information on socio-economics and institutional and legal aspects appear to be completely ignored (Mukherji and Shah, 2005; van der Gun and Lipponen, 2010). The knowledge gap is the communication mismatch between the producers and users of information. Often it is the producers of information that have defined which and how information is being produced and disseminated without taking into account the mind frames of the users of the information (Timmerman and Langaas, 2005). Translation of technical information into understandable information for non-experts is generally weak. Groundwater management often lacks the financial and human resources needed for the investigation of the resource characteristics and functions, especially in developing countries, and as a consequence there are shortcomings in terms of reasonable legal provisions and pricing systems. In many instances groundwater experts are unwilling to share information with the general public (Knueppe, 2011). Sometimes countries are unwilling to share data and information on groundwater resources because of national security arguments.

8.6 Limited mental models and framing of groundwater resources

It is being increasingly recognized by scientists that groundwater resources are complex adaptive systems. To provide sustainable and equitable solution to groundwater-management issues requires a holistic approach based on the knowledge and expertise of many disciplines. However, human actors typically tend to reduce the complexity and dimensions of such complex problems. What may be more appropriately described as a messy problem situation is often compressed into a description of a well-defined problem with simple cause-effect relationships (Pahl-Wostl, 2007). It is an incorrect assumption that there is a single perceived characterisation of the scale and level a phenomenon is working on. The drive to frame issues at a single scale or level comes from the need to both simplify and control (puts it under the sole responsibility of one group (Cash *et al*., 2006).

However, often groundwater resources systems are still considered to be systems that can be managed by a plan and control and engineering approach. Departments responsible for the management often hold a small diversity of disciplines with a bias on technical sciences and engineering solutions (Pahl-Wostl, 2007). In the traditional groundwater communication, there is a bias on addressing negative consequences of overexploitation instead of addressing the socio-economic benefits of using groundwater resources. Mental models and framing in groundwater resources management are very much determined on the uncertainty and mystical characteristics of the groundwater resources, besides cultural backgrounds and subjective preferences and prejudices (Milman and Ray, 2011). These mental models around groundwater shape perceptions of equity, sustainability and issues of use across borders.

8.7 Lack of sufficient public participation

The involvement of stakeholders in policy-making processes and resource utilization is mostly weak and barely acknowledged by groundwater managers and government agents (Knueppe, 2011). Civil servants are often not trained to deal with processes that include interaction with communities. There are often few regulations in place that recognize the power or mandates of civil society organizations and they are even seen as activist or even illegal interest groups. Often civil society is poorly developed. People do not have the capacity or time to be involved in all nor do they have adequate access to information, which may impede multi-scale participation (Theesfeld, 2010). There is a lack of knowledge on the technical groundwater issues with citizens at grass-root level and in the staffs of NGOs and CBOs. Marginalized and minority voices may be excluded from participation (Garduño *et al*., 2010).

9. Knowledge gaps: Identifying what we don't know

There are still large areas about which we do not possess adequate information or understanding in the context of groundwater governance. Perhaps the most unknown factor of groundwater governance is the resource itself (Mukherji and Shah, 2005; Villholth, 2006; Theesfeld, 2008). The intrinsic complexity and heterogeneity of groundwater, combined with the relative inaccessibility for monitoring results in cases where many of the groundwater system and aquifer characteristics like its dimensions, storage and conductivity properties and rates of recharge and discharge, are poorly known (Milman and Ray, 2011). Without these basic data on groundwater quantity and quality, it becomes very hard to estimate socially constructed concepts and indicators like safe yield and groundwater sustainability that are used by those responsible for developing sensible groundwater policies and managing the resource.

Relevant socio-economic information related to groundwater is especially missing (Shah, 2007) and where the administrative capacity to register and monitor the groundwater development by new users is lacking, the accumulated groundwater demand is hard to estimate. In many cases it is unknown to those responsible for governing the resource how many people are depending on it and to what extent. Do they depend on groundwater for daily survival as alternatives are simply lacking or does groundwater form an important input factor to sustain livelihoods (e.g. based on groundwater based agriculture)? Additionally, governments are often only able to roughly estimate how their national economies depend on groundwater resources.

In addition, although it is fairly well accepted that more general water sector decisions and policies are likely to highly impact more national and local actions, most countries lack the research capacity to study and determine the causality and dynamics between macro-policies, such as food security, energy security, international trade, and spatial planning, and groundwater policy. Hence important links, trade-offs and possible synergies and opportunities are missed and suboptimal or even decisions counter-acting sustainable, equitable and effective groundwater resources management are taken (UNDP WGF 2011; Shah, 2007).

Finally, the institutional diversity of groundwater governance models is enormous as the small set of case studies in section 7 perfectly illustrates. Yet, we do not have a complete picture of the institutional diversity and management practices in groundwater governance. Groundwater governance studies thus far have only looked at comparisons of just a selected small number of cases and/or focussed on particular governance issues. It is unclear how some the institutional solutions and principles, which are generally advocated to facilitate the implementation of good groundwater governance, work out in practice across a variety of settings. For example, decentralization of groundwater management roles and responsibilities to lower scale organizations is thought to foster context–fit and demand-responsiveness but if economies of scale are missed, the decentralization may ultimately come at a higher cost. Public participation is another solution propagated to facilitate good groundwater governance. However, research on public participation has shown that it is a process with variable success rates because of issues of unwillingness, indecisiveness and inability at all kinds of levels and scales (Meinzen-Dick, 2007). Similarly, the institutional reform of privatizing water utilities that were part of the earlier neo-liberal paradigm on water was originally advocated to be the most promising solution to provide effective and efficient water services. Yet current evaluations of privatizations of governmental water services across the globe show varying levels of success and failure (Budds and McGranahan, 2003; Prasad, 2006). Although it is assumed that eventually the transaction costs of managing water resources will decrease when good water governance practices are applied (UNDP WGF, 2011), we know far less about the transaction costs associated with transitioning to new governance structures and applying broader practices to a more local context.

With groundwater governance being a social construct based on a set of interrelated and sometimes changing principles norms and values, it is assumed that it is, like other institutional changes, path-dependent (Shah, 2007). Countries that currently appear to have a similar groundwater governance status will likely evolve differently because of decisions taken in the past. A groundwater decision taken by a country that appears to be in a context similar to a former context in a different country will likely turn out differently. However, the generally increasing global connectivity between and shared by various groundwater communities of practice may decrease these differences.

Importantly, the knowledge gaps on groundwater governance highlighted here should not serve as an argument to delay action. No situation should be created where there is "paralysis by analysis" (Wade, 1988). Neither should we have unrealistic high expectations of success of implementations of various groundwater governance mechanisms. Meinzen-Dick (2007) puts it rightly when she states that rather than adopting rigid institutional models and then declaring each of them to be a failure, it is better to make explicit provision for institutional learning and change.

10. Evolution of successful and unsuccessful paradigms, models, instruments, and methodologies

Based on the described case studies and the diagnosis of barriers and opportunities in groundwater governance, this section tries to synthesize the evolution of various groundwater governance paradigms and to determine its level of success. One of the assumptions taken here, as already mentioned earlier in the introduction, is that the paradigms to govern groundwater are nested within those that govern water which are again part of or closely linked to paradigms on how we deal with natural resources in general. This section takes a classical separation of state, market and collective action paradigms to natural resources.

Historically, the state has always been involved in developing and managing water resources by providing the engineering capacity. This engineering-based and hydro-centric approach peaked during in the period of Industrial modernity when it was generally believed that with capital and technology one was able to control nature (Allan, 2005). During the hydraulic mission, many governments constructed large water infrastructural works and developed water resource for the benefit of society and economic development. Foster (2006) describes that countries during this phase often go through a process from groundwater under-utilization to a stage of over-exploitation where negative impacts become apparent. Although nowadays this approach is considered non-sustainable, it must be acknowledged that this paradigm has contributed to the economic development of many countries across the world (Mukherji and Shah, 2005; Björklund *et al.*, 2009).

From the 1980's, the human confidence in nature's predictability and controllability was declining. The scientific application of the systems approach to natural systems raised the recognition of limits to growth. Furthermore, neo-liberalism questioned the affordability of state-driven water resources development and other public services provision. In the field of water management, this resulted in a paradigm change towards IWRM, which has been successful in implementing notions of sustainability. Many examples can be found where IWRM has been able to slow down or even reverse negative impacts of groundwater use. However, full IWRM often requires a large institutional restructuring of rights systems, markets and the establishment of aquifer basin authorities with sufficient regulatory power and resources. Only a few (often developed) countries have had the ability to bear the necessary transaction costs. Other countries especially in the developing world have continued with the hydraulic mission (Allan, 2005) or take a "clumsy" approach where they incrementally try to install bits and pieces of IWRM (Moench *et al*., 2003). Groundwater issues that still tend to be under-addressed (even in the counties where a relatively full IWRM approach has been taken) are groundwater quality and groundwater and urban development (Foster and Chilton, 2003).

IWRM's goal to gain full understanding of natural system dynamics can hardly be met in practice because of intrinsic unpredictable character of nature and the limited resources available for the monitoring which is a prerequisite for this understanding. The adaptive water management approach that is currently advocated takes these limitations into account. A more learning-by-doing (and monitoring and evaluating) model forms its basis. The effectiveness of this approach still remains to be proven. The coming decades of climate change will provide a huge test case.

Market solutions towards groundwater resources management appear to be applied only limitedly and have been variably successful. In many countries, groundwater rights even changed from originally being private property rights towards usufruct rights putting the groundwater resource itself under state property (Gupta and Lebel, 2010). Neo-liberalism thinking pushed many countries to privatize their water utilities to some extent (Solanes and Jouravlev, 2006). This has been limited mostly to drinking water supply companies. Studies from the United States and other parts of the world have indicated that the large capital investments needed, coupled with the open access characteristic of aquifers and the economic characteristics of the agricultural sector, make private investors reluctant to develop risky groundwater-based irrigation services to farmers. Water markets are seen as a promising instrument to allocate water sustainably and economically while preserving notions of fairness (Zetland, 2011). The trading of capped groundwater allocations can reduce the cost of limiting water use (Thompson *et al*., 2009). However, water markets that lack some level of governmental regulations and/or guidance are deemed to behave less well.

There is a large volume of literature on the efficacy of collective action or community-based management of natural resources. Grabert and Narasimhan (2006) note that although success stories are limited, collective action was the only option that did work. Some critics argue that many of these community-based management approaches lack a regional overview, technical knowledge and resources to properly monitor and hence fail to take into account environmental externalities (Blaikie, 2006).

The conclusion is that there is no single paradigm, model instrument or policy that has been generally successful. There are no panaceas (Ostrom, 2007) when it comes to effective, sustainable and equitable governance of natural resources like groundwater. Contexts and historical development paths (Shah, 2007; Solanes and Jouravlev, 2006; Villholth, 2006) determine the applicability and potential success of the various mentioned groundwater governance and management instruments. Groundwater is mostly a local issue and solutions need to be found that are fit to that location including vague and often immeasurable notions like societal culture and the sign of the times. Per definition, as these notions change, paradigms that are social constructs change as well. Secondly, only very few cases are known where groundwater governance have been either fully state, market or collective action driven. Often these three groundwater-governance paradigms have existed and have been practiced simultaneously in some hybrid and nested form all the time. By accepting the complexity of groundwater resources management and recognizing that the different paradigms and approaches all have a role, good groundwater governance practices can be developed.

PART 3: PROSPECTS

11. Significance and options for groundwater governance and policy: operational definitions for the GWG project

Governance, as we have seen, can be defined as "the sum of the many ways individuals and institutions, public and private, manage their common affairs" (Saunier and Meganck, 2007). Under a governance approach, considerable attention is given to the interactions between the variety of policies, decisions and enforcement practices (Tesiman and Hermans, *In*: van der Valk and Keenan, 2011). In this forward-looking part of the paper we consider prospects for future modes of groundwater governance that will prove to be robust and sustainable. In doing so, we note that groundwater governance occurs in the context of broader governance trends. These trends include macro-economic policies at all levels, the widespread adoption of integrated management, the growing involvement of civil-society and other non-state institutions in environmental decision-making, and the recognition of demand-side management as a complement to traditional supply-side approaches. The implementation of successful policies will require decision-makers and on-the-ground implementers to reassess the classical toolbox for groundwater managers within a broad context.

One of the most pervasive notions of past governance modes has been the overriding prevalence of technical and scientific approaches. Such approaches have of course contributed immensely to our understanding of groundwater systems and provided productive ways to harness their resources. But, at bottom, governance increasingly has come to be seen as a political concept in which the chief constraints are social, institutional, and political (Linton and Brooks, 2011; Burke *et al*., 1999; Burke and Moench, 2000; Linton, 2010; Espelend, 1998). Viewed in this light, changes in governance — of groundwater resources or indeed of any process —necessarily involve changes in power relations. Accordingly, when such actions as decentralization, public participation, and conservation are proposed, it is unsurprising that these often meet with scepticism and even resistance. A clear lesson is that changes in governance are long-term processes that should be incrementally developed and that are accompanied by high transaction costs.

One characteristic of governance that contributes to high transaction costs is the high degree of interrelatedness, dependency, and mutually reinforcing nature of governance. These features are incapable of standing alone. For example, accessible information means more transparency, broader participation and more effective decision-making. Broad participation contributes both to the exchange of information needed for effective decision-making and to the legitimacy of those decisions. Legitimacy, in turn, means effective implementation and encourages further participation. Responsive institutions must be transparent and function according to the rule of law if they are to be equitable. These core characteristics represent the ideal; no one society has them all.

Among the tensions generated by the above features of groundwater governance is the question of the locus of policymaking. At one extreme, such policymaking is subject to the broad role of institutions and rules that govern behavior. These may be global or regional and they may involve international treaties. Or they may be national. GW-MATE's (Groundwater Management Advisory Team; 2004) operational experience shows that a decentralised groundwater management with some form of stakeholder participation is the most promising approach. Ideally, our review of the literature suggests that groundwater management and its associated policy-making should be performed at the lowest scale possible, that is, at the local level and so as to fit the context. This context includes culture, religion, the role of the state, specific resource conditions, historic water use patterns, relative capacity of actors, attitudes toward groundwater, existing scientific paradigm, heightened dependencies, and indeed, any variables that affect policy (Ostrom, 1990; Ostrom, 2007).

But in our preference for actions at local scales, we should recognize that such actions are always embedded within higher scale processes, possibilities, and restrictions. Equally important is to have coherence of groundwater policies across all scales. As an example, international lawyers consider international agreements as the most logical instrument to manage transboundary water conflicts. Such agreements are useless when not supported by domestic legislations and local users adhering to it.

Groundwater governance also should be viewed in close relationship with national or even international policies on food security and energy security. With agriculture often being the biggest groundwater consumer and with increasing competition with bio-fuels, a country's choices to be self-sufficient can have immense consequences. Optimizing groundwater demand with virtual-water transfer mechanisms often has bigger effects than sophisticated water saving measures. Obviously, the ambition to reduce groundwater demand should be balanced with potentially unwanted loss of agriculture-based livelihoods and economies. Accomplishing such outcomes will entail employing the full arsenal of conventional groundwater policies such as well registration, licensing, monitoring, education, voluntary compliance, and enforcement. But in as noted above — while recognizing that there are no one-size-fits-all modes of governance — such steps should strive to fit local contexts and historical development paths (Mukherji and Shah, 2005; Ostrom *et al*., 2007; Theesfeld, 2008; Villholth, 2006). As one example of how circumstances differ by region or country, data for 18 countries show great variability in irrigable area equipped with a groundwater source, ranging from a low of 18 percent (Afghanistan) to a high of 97 percent (Saudi Arabia) (FAO Aquastat, 2011). Clearly, groundwater policies will vary by region.

In view of the changing understanding of governance — that is, its evolution from a technical process to a socio-political one — it is important to consider overall perceptions of groundwater. Some observers have noted that in many societies, this perception is largely negative (e.g. Knueppe, 2011). To counteract such notions, it is important to inform water users about the value of groundwater and aquifers. Although quantifying the value of groundwater remains elusive, expressing it in monetary units would be most persuasive to decision-makers operating in resource-deficient environments. Such a course would help build support for more forward-looking and sustainable groundwater governance policies. Moreover, UN-system agencies and other organizations can help to harvest and disseminate lessons from the many governments and communities around the world that are trying different approaches to groundwater governance (Moench *et al.*, 2003).

12. Criteria and Considerations for Effective Policy Objectives and Groundwater Governance

In order to avoid what has come to be called "the tragedy of the commons," some sort of common property regime or "unitization" agreement will have to be established and fostered for groundwater resources as they have been for other open-access resources (Linton and Brooks, 2011; Ostrom, 1994; Agrawal, 2001; Weaver, 2011). Such regimes will require that that resource users and managers develop common rules for exploitation that apply at the scale of the aquifer, something that is bound to be more difficult across an international border. In a different context, Bakker (2007: 447) has advocated recognizing and empowering alternative concepts of property rights, most notably in the form of what she calls "community economies of water." The principles of governance that we are advocating in this paper would help provide a basis for establishing such regimes. At the aquifer level, Aquifer Management Organizations, comprising representatives of government agencies, water users and other stakeholders, may play important roles in the implementation of planning determinations and management measures (Foster and Loucks, 2006). In the context of international aquifers, it is helpful to think about mediation and conflict resolution and the broader role of national economic or military security issues in negotiations and management (Blomquist and Ingram, 2003).

Under the scope of the broader regime, it is important to consider compliance issues. Groundwater, unlike surface water, is subject to the individual decisions of hundreds or even perhaps thousands of independent users with direct access to the resource. Because of this, top-down control has often proven insufficient in many places and the reason why user communities are often advocated as the most plausible solution to ensure adequate groundwater resources management (Llamas and Martínez-Cortina, 2009: 198). Groundwater governance should be based then on voluntary compliance due to the immensely high transaction costs of rule compliance and enforcement. Voluntary compliance is fostered when the groundwater rules are demand responsive, align with local norms and beliefs, provide for conflict resolution and implicitly assume a common level of understanding of the resource systems, its issues and solutions (Theesfeld, 2010).

In addition to Ostrom's (1990) design principles and formal rules, increasingly scholars and observers are recognizing that sustainable groundwater management depends on a flexible and adaptive management approach. Such an approach should feature strong collaboration between scientists, policy makers, water supply agencies, and water users. This is an effective way to deal with externalities, to bring in the necessary technical knowledge, and to be able to make use of economies of scale that allow affordable monitoring and surveying (Ross and Martínez-Santos, 2010) . A fundamental challenge is to design institutions that are not vulnerable to capture by subsets of the community that self-organize to direct the institution against the overall social interest. In a world of episodic structural change, such as social-ecological systems, adaptive learning can lock in to a single institution, model, or parameter estimate. Policy diversification, leading to escape from panacea traps, can come from monitoring indicators of episodic change on slow timescales, minimax regret decision-making, active experimentation to accelerate model identification, mechanisms for broadening the set of models or institutions under consideration, and processes for discovery of new institutions and technologies for ecosystem management (Brock and Carpenter, 2007).

13. Applying Practical Policy Principles for Groundwater Governance

Ultimately, effective governance will be dependent upon sufficient capacity to generate the interactions and actions necessary. In the context of water governance, capacity is about the "ability to generate clearly different roles for all in such a way that the actions lead to interaction patterns with maximum outcomes against affordable efforts" (Teisman and Hermans, *In*: van der Valk and Keenan, 2011). Communities across the globe will need to invest in a number of governance capacities that will enable them to integrate the legal, managerial, financial, institutional, and social elements integral to effective water governance (Satijn and ten Brinke, *In:* van der Valk and Kennan, 2011). These investments will help to promote both processes for governance as well as structures to ensure appropriate implementation and evaluation. Below we outline some practical policy principles for groundwater governance that build from the broader observations outlined above. It is important to recognize that few water governance institutions or processes will meet the ideal but rather we present these principles as action steps that have deemed important to effective governance.

13.1 Role of governmental groundwater resource management entities

There is no one-size-fits-all answer to meet groundwater governance challenges, but some overarching principles can be identified to improve water governance.

- A key institutional requirement in many countries for improving groundwater management at field-level will be to transform the role of the government agencies responsible for groundwater from exclusively 'supply-development' to primarily 'resource-custodian' and 'information-provider', and to ensure that such agencies fully engage groundwater users and stakeholders in a participatory management process (Foster, 2006; Garduño *et al.*, 2010).
- Important roles for national governments to ensure strong state/provincial level agencies include:
    - allocating sufficient financial resources and removing bureaucratic obstacles to hiring the required professionals, and recommending adequate salaries and career development (such that they are less vulnerable to corruption)
    - establishing guidelines to address the management of trans-state and internationally-shared aquifer systems
    - providing minimum reference standards for the identification, characterisation, monitoring and evaluation of groundwater basins 'at risk', and defined procedures for the specification and implementation of management measures appropriate to the level of risk involved
    - diversifying the curricula for hydrogeologists to include more social sciences (FAO, 2011 Draft Water Tenure Guidelines: 52) and policy
- Realign the responsibility of management of water resources within ministries of environment and other agencies that may be outranked by institutions such as ministries of finance, trade, agriculture, mining, industry, or public services, and attempt to ensure sufficient influence to negotiate effectively with the more powerful entities.
- Separate policy-making from the operational management and provision of water services of different entities and make their links and roles clear (Solanes and Jouravlev, 2006).
- Adopt governance instruments to foster coherence across water-related policy areas and between levels of government, and assess their effectiveness in coordinating water policy at horizontal and vertical levels (OECD, 2011).
- Ensure that agencies and ministries have the necessary capacity and policy-making power (Solanes and Jouravlev, 2006).
- Recognize and tackle the bureaucratic inertia (change of formal rules) and political reluctance or even obstruction and facilitate processes to counter these obstacles (Theesfeld, 2008).
- Link to larger macro-level policy decisions to help strengthen groundwater governance (Garduño *et al.*, 2010). There is large potential to indirect management of groundwater resources by affecting the policy on food (virtual water, increase productivity), energy and trade (Mukherji and Shah, 2005). Undertake a comprehensive review of policy and legislation to examine how existing frameworks support the responsible groundwater governance and make policy and legislative modifications as appropriate.

13.2 Role of information and science

- There is strong need and potential for the development of national research programmes to gather representative groundwater data directly in countries and regions where dependence upon groundwater is high (Mukherji and Shah, 2005). Governments should commit themselves to provide sufficient resources for groundwater monitoring and assessment.
- There is an increasing availability of Remote Sensing-images which can help estimate the surface components of groundwater systems such as recharge and discharge and support those groundwater resource managers that lack in-situ monitored data. Remote-sensing images, which can be used rather inexpensively or at no costs, can also be used in negotiations on groundwater resources allocation as they provide impartial proofs of land use.
- Socio-economic information, which plays a more subtle role related to poverty alleviation, health standards and social vulnerability, should also be collected (Knueppe, 2011; Mukherji and Shah, 2005; Moench *et al.*, 2003). Assessing the effectiveness of water information systems and databases in bridging the information gap is a difficult task but OECD evidence shows that hydrological and physical water information is far more advanced and accessible than economic and financial data to guide decision-making (OECD, 2011).
- Collaborative efforts for the acquisition and sharing of hydrologic data and information can serve to overcome institutional asymmetries (Megdal and Scott, 2011). Scientific and technical data may also serve to facilitate negotiations on water allocation and coordination of management roles and help resolve conflicts and disputes (Moench et al., 2003).
- Global organizations like UNESCO-IHP, IAH, FAO and bridging organizations like IGRAC need to continue spreading this message and facilitate countries to make it work. The international community, acting through bilateral and multilateral aid mechanisms, should provide greater support for data collection and management (FAO, 2011 Draft Water Tenure: 51).
- In countries that lack basic hydrological data, a greater investment in data collection and data management will be necessary (FAO, 2011 Draft Water Tenure: 51).
- Create early warning systems based on indicators to assist with disaster-preparedness. Because adaptive approaches do not require full understanding of resource dynamics and build off coping strategies that populations are already engaged in, such approaches may be able to produce 'results' more rapidly than they can be integrated into management initiatives. In addition, they often do not require the introduction of new institutions (such as water rights) and may be able to minimize politically difficult decisions (such as extraction controls) in the short term. This is important because the institutional capacity and data essential for active integrated management of the resource base is absent in many countries and could take decades to develop (Moench *et al.*, 2003).

13.3 Role of public participation

- Since groundwater management is more about influencing the behaviour of individual groundwater users and potential *p*olluters, than top-down allocation of a clearly-defined natural resource, the process of enabling and nurturing stakeholder participation is an especially critical groundwater governance instrument (Garduño *et al.*, 2010)
- Leadership in groundwater governance is essential for planning and implementation processes and to facilitate communication between all of the relevant stakeholders, sectors and governmental agencies, and to support information exchange between stakeholders and national governments (Knueppe, 2011).
- It is necessary to train the staff of NGOs and citizen groups on both technical groundwater issues and on policy and policy-making techniques.
- Develop and enable community-management of groundwater resources (which includes training and organization of the community, training of the civil servants in guiding public participation processes and formal establishment of the different roles and responsibilities and accountabilities of the various groups in policies and regulations) (Mukherji and Shah, 2005).
- Expand opportunities for public participation: The UN Economic Commission for Europe's "Aarhus Convention" (1998), a multilateral environmental agreement through which the opportunities for European citizens to access environmental information are increased and transparent, may serve as a model for others. It is a way of enhancing the environmental governance network, introducing a reactive and trustworthy relationship between civil society and governments and adding the novelty of a mechanism created to empower the value of public participation in the policy-making process and guarantee access to justice.

- Modern information technology such as internet and social media can also serve to greatly improve the connectedness of various groundwater groups of stakeholders across the world (Villholth, 2006). Such virtual media enables such groups to form communities of practice and exchange and discuss on norms, values, preferences, experiences, success and failures, lessons learnt knowledge, information and data. The conference of parties are part of so-called social learning processes, which are assumed to lead to confirm and change social practice and the associated interpretation of the environment (Pahl-Wostl, 2007).

13.4 Role of scale and fit

- Continuously analyze the impact of the existing and proposed macro-policies on water development and use and keep an open and frank dialogue with those responsible for creating and implementing the policies (Solanes and Jouravlev, 2006).
- The national government can promote bottom-up approaches by playing an active role in the mobilisation of people in local processes, providing funds and technical services for local initiatives, investing in infrastructure, building capacity and expertise among practitioners, and coordinating initiatives that span more than one local government.
- Strive to build coherence across scales (Hoff, 2009). To better achieve vertical integration of governance systems across levels, water management should be coherently addressed by local action (such as land and water use), national policies (such as agricultural or export subsidies), and international agreements (such as protocols to the climate convention or trade regimes).
- Utilize global policy networks to help achieve smarter horizontal governance approaches.
- Multi-level governance capacities increase when actions across levels and across domains of content and responsibility are sufficiently aligned (Gupta, 2011).
- Craft bridging organizations that manoeuvre between scales and international groundwater initiatives to help play an intermediary role and promote the co-production of knowledge (Cash *et al.*, 2006; Vilholth, 2006).
- Create governance instruments to address the mismatch between hydrological and administrative functional units (OECD, 2011).

13.5 Role of Economics

- Use economic incentives to steer changes of individual users' behaviour but also change in institutional behaviour (Hoff, 2009).
- Develop best practices guidelines to incorporating the scarcity value of water in water pricing.
- Develop best practices guidelines for recognizing third-party impacts, and then utilize this information in developing water-management policies.
- Develop market approaches to optimize water allocation and the provision of water services and the management of the resource but never without governmental guidance that regulate potential market distortions (Solanes and Jouravlev, 2009).

14. Way forward—Set of Practices for "Responsible Groundwater Use"?

We opened this paper by pointing to the large, remaining gaps in our understanding of how water is an integral part of society and its relationship to the planet's environment. The concept of sustainability offered an opening for formalizing this connection and recognizing that water is a fundamental human value as well as a critical resource. Going further, we have recognized that, at their root, all modes of tapping, distributing, and managing water supplies are the result of organized human effort, usually achieved through institutions.

We have termed this enterprise governance. It applies equally to surface water and groundwater, and in this exercise we have addressed the role of governance of subsurface water, which according to many practitioners and observers remains largely uncharted, incompletely assessed, and notably uncertain and complex. As a result, because our understanding of groundwater systems is incomplete, the design of suitable approaches to and paradigms for governance is a work in progress.

In the course of reviewing the literature and assessing prevailing notions on how groundwater is being governed across the globe, we have sensed a very palpable rise in the recognition of the centrality of governance. It's difficult not to notice how far we have come since the days when water management was left solely to engineers and technocrats.

Our purpose here has been to discover principles, knowledge gaps, challenges, and perhaps most importantly, lessons learned. By analyzing these lessons — both positive and negative — through the medium of case studies and other practical and theoretical findings, we have attempted to uncover a set of practices that with luck may guide the way to "responsible groundwater use." These practices, if they are to succeed, will need to be flexible, responsive, incremental, cost-effective, culturally sensitive, equitable, and politically astute. Put another way, they will have to factor in the dynamics — that is, the prevailing physical and societal driving forces — and the desires and vagaries of human and institutional behaviour in the particular social-process system in which the management of water is embedded. In other words, insofar as feasible, governance should strive to be context-based and adaptive to the greatest degree possible.

Accordingly, to achieve long-term sustainability of groundwater management (and water management, in general), each country will have to govern its water resources within its own financial, technological, and institutional capability, and strategically use available international resources. This calls for considerable ingenuity at the appropriate governance levels to figure out the most appropriate ways of proceeding in specific contexts.

Finally, following Ostrom *et al.* (2007), we recognize that prescriptions for sustainability and good governance should be accompanied by a healthy measure of modesty by observers whose intended panaceas too often prove naïve in real-world settings.

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Legal and Institutional Framework

Digest

Relevance

Legal frameworks play a crucial role for effective groundwater governance. They provide the basis and starting point for policy development and they turn policy decisions into rights and obligations. The legal framework for groundwater management should regulate access to groundwater resources, set criteria for allocation, deal with protection against depletion and pollution, establish monitoring and planning tools and stipulate stakeholder participation, among other issues. Worldwide it has become the dominant legal paradigm to introduce modern water legislation with permit-based systems of administrative water rights at their core to address these issues. At the same time customary, community-based and informal arrangements continue to govern access to groundwater in large parts of the world, particularly in the rural areas of developing countries, instead of, besides or despite of formal legislation.

When transboundary aquifers are concerned domestic legislation has to be compatible with rules of international water law, which determine states' rights and obligations. International groundwater is still at a nascent stage. While for the 263 river basins hundreds of treaties have been concluded, only five of the 273 transboundary aquifers are addressed in specific legal arrangements. In the absence of a regional or global treaty the 2008 Draft Articles on the Law of Transboundary Aquifers, which were adopted by the United Nations International Law Commission and taken note of by the United Nations General Assembly, represent the most authoritative codification of international groundwater law. The paucity of international instruments addressing transboundary aquifers reflects longstanding disregard and partly ignorance of the shared nature of these resources which has only recently begun to change.

Coverage

Part 1 (Baseline) of the Thematic Paper 6 on Legal and Institutional Frameworks provides an overview of the main features of legal and institutional frameworks on groundwater first with respect to domestic law, addressing both formal and customary approaches, then with respect to international law. Part 2 (Diagnostic) discusses key challenges that have to be addressed if legal rules are to make a more effective contribution to getting a handle on aquifer depletion and degradation – again both with respect to the domestic and the international plane. Part 3 (Prospects) looks into the future and suggests issues whose relevance is likely to increase. The Thematic Paper focuses on the use of groundwater for human consumption, agricultural, industrial and environmental purposes. The legal challenges arising from newer technologies such as those related to the use of geothermal energy, carbon dioxide capture and storage (CCS), and hydrofracturing ("fracking") to capture shale gas, where in many cases specialized laws and regulations still have to catch up with technological developments, are only touched upon in passing.

Key Issues and recommendations

Domestic level

Groundwater as a public good. There is a worldwide trend to vest ownership of or control over all water resources in the state as a guardian or trustee and to separate it from ownership of the overlying land. Groundwater becomes a public good and a permit is required to obtain a right to abstract it. This is the first step of introducing a system of formal water rights that allows the government to manage and protect groundwater resources in the interest of the public. In important countries where groundwater is formally a public good it continues to be perceived as an intensely "private" good. Such perceptions interfere with compliance or generate transition problems from an unregulated to a regulated regime and can be a strong driver for overexploitation.

Appropriate and coherent frameworks. The central elements of modern water legislation are well known. They comprise, inter alia, the regulation of drilling and drillers, the granting of water abstraction permits, requirements to meter wells and the recording of permits in a registry. Water laws also deal with protection against depletion and pollution, establish monitoring and planning tools and stipulate stakeholder participation. Administrating such legislation, and in particular permit systems, is a costly, administratively challenging and time-consuming process.

In many jurisdictions groundwater legislation remains incomplete, outdated, or inconsistent with surface water law, land law or environmental law. Such shortcomings may in certain situations be best addressed by introducing a new comprehensive water law dealing with all water resources of a country in one piece and enshrining principles of integrated and sustainable water management as part of a more substantive water sector reform. In other situations it might be more advisable to take smaller steps or to take a staged approach. In all cases the legal mechanisms created should be accountable, transparent and participatory. Transition processes have to be carefully managed, including by involving stakeholders, and existing rights have to be protected.

De minimis use. The degree of complexity of water legislation and in particular of a permit system must be commensurate with the available institutional, planning and administrative capacity. For administrative convenience and cost it is standard practice to exclude from permit requirements small-scale or d*e minimis* uses who use water for drinking, watering domestic animals, meeting of basic household needs, or the watering of garden plots. Defining the threshold for *de minimis* use is a tricky task because the accumulated effects of unregulated small-scale use may generate significant negative environmental impacts where water demand outstrips supply.

Customary rights. In many parts of the world customary or local water rules effectively guide the way individuals use groundwater and are perceived as the legitimate rules in place. However, they are often not sufficient to cope with growing pressure on water resources induced by technical innovation, socio-economic drivers or environmental changes and do not provide the legal security needed for large investments. Their relationship and interplay with formal legislation invariably tends to be unclear and complicated. Where a formal water management framework is introduced it should respect and protect existing rights, avoid disenfranchising customary rights holders and take into account existing perceptions, values (water as a common property) and structures but also enable groundwater management decisions beyond the local level and require permits for certain types of uses.

Land-water interface. Managing groundwater requires taking into account the land-water interface as groundwater quantity and quality protection are affected by land management. Natural groundwater recharge processes have to be protected from land-based interference and the intricate problem of land-based diffuse pollution, particularly from agricultural run-off, has to be addressed. Among the legal measures used to protect groundwater against detrimental land uses are the prohibition or limitation of certain polluting activities; limitations of the use of fertilizers and pesticides; prohibition or limitation of certain water-using activities; restrictions of certain cropping patterns; reduction of animal-grazing intensity; and land reclamation and drainage. Also land surface zoning is often applied to recharge areas, in particular with a view to protecting drinking water sources, but also to other critical areas of high vulnerability. It becomes increasingly important to both develop and coordinate land use plans, in both urban and rural areas, with river basin or aquifer development plans.

Stakeholder participation and (ground-)water user groups. Rules on stakeholder participation and (ground-) water user groups have become standard features of groundwater legislation. The legal framework has to provide options how users can organize and clearly define the role and responsibilities of groundwater user groups on the one hand and the water administration and other public institutions on the other. Among the organizational forms available are water users associations, groundwater user groups, village water supply groups, aquifer management organizations (AMORs) or NGOs. The governance arrangements that may work across a small aquifer may not work in large aquifers supplying water to a range of different activities in larger urban, agricultural, industrial and mining areas.

Implementation and enforcement. Implementation is the key for any working water law regime. Implementing groundwater legislation is particularly challenging because of the sheer number of users involved, monitoring difficulties and the high financial implications. Constraints to implementation are legal requirements that exceed the available technical, human and financial resources; formal legislation that is not well aligned with customary or local rules and thus rejected; and insufficient information on groundwater resources that impedes informed decisions about allocation and protection measures.
Institutional mechanisms tend to lag behind the tasks created by new legislation. In many countries there is still a fragmented institutional structure, often with one ministry or authority being in charge of surface water and another (typically less well staffed and financed) of groundwater. Gaps and overlaps in competence as well as lack of coordination horizontally among different ministries and authorities or vertically cross different levels e.g. from the federal to the state level, may render the implementation of legislation cumbersome or ineffective.

Setting up accountable and transparent institutional arrangements, staffing them with skilled personnel and financing them appropriately takes time. It is important to stage the steps of introducing new rights and obligations appropriately in order to avoid signals of non-implementation and to ensure that non-compliance incurs sanctions. With patchy enforcement those who do not respect the law are often not sanctioned, thus deterring the rest of the user community from complying as well.

Water law and macro-level policies. If water law is to make an effective contribution to good groundwater governance, water law and policy and social, economic, agricultural and environmental policies need to be aligned. Where economic triggers to overexploit groundwater (such as subsidies on energy tariffs) and technological innovation meet weak water law implementation, the result is aquifer degradation.

International Level

Agreements for specific aquifers. Specific agreements have been concluded for the Genevese Aquifer, the Nubian Sandstone Aquifer, the North Western Sahara Aquifer, the Iullemeden Aquifer and the Guaraní Aquifer. Some of these address only rather limited technical issues, some have not yet entered into force. A number of bi- and multilateral treaties for specific rivers and lakes also contain provisions on groundwater.

Regional Instruments. The most advanced regional regimes have been developed in Europe under the auspices of the UNECE and the EU. The 1992 UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes (also referred to as the "Helsinki Convention") is the central UNECE instrument. Model provisions on transboundary groundwaters to supplement it are currently being developed. For members of the European Union (and candidate countries) the 2000 Water Framework Directive (Directive 2000/60/EC) provides for a detailed, encompassing and most advanced regime of quantity and quality protection of all waters – rivers, lakes, coastal waters and groundwater, domestic and transboundary – and sets the parameter for the water policy of each member state. By 2015, all groundwater has to achieve "good groundwater status", which is defined in terms of both quantity and chemical status. In 2013, a new daughter directive to the Water Framework Directive on the protection of groundwater against pollution and deterioration (Directive 2006/118/EC) will enter into force.

The global level. The main international water treaty, the 1997 United Nations Convention on the Non-Navigational Uses of International Watercourses, excludes non-recharging (fossil) aquifers from its scope and does not address groundwater in its substantive provisions. To fill this gap the International Law Commission of the United Nations adopted in 2008 a set of 19 Draft Articles on the Law of Transboundary Aquifers. The UN General Assembly took note of the Draft Articles and encouraged States to make appropriate bilateral and regional aquifer arrangements taking them into account. Although of a non-binding nature, the Draft Articles are the most authoritative statement of the international law of shared groundwater resource until present.

Sovereignty. Both in the Draft Articles and in the 2010 Agreement on the Guaraní Aquifer strong emphasis has been placed on the issue of sovereignty over aquifers, which has been sharply criticized by many as being a retrogressive step in the law of shared freshwater resources.

Cooperation. Cooperation can generate the most tangible and short-term positive impacts on groundwater governance at the level of specific transboundary aquifers. Where a treaty seems one step too far or too cumbersome an incremental approach or more informal arrangements not (yet) backed by formal legal instruments or priority action along the border region can be useful options.

Benefit sharing and other lessons learned. Cooperation over transboundary aquifers takes place only where all sides benefit from it. Other key factors for working treaty arrangements distilled from studies of transboundary freshwater and marine legal and institutional frameworks are information and data exchange, the existence of a dispute resolution mechanism, sustainable financing, good institutional design at the technical and political level, the adaptability or flexibility of the treaty and public participation.

External support. With the exception of the Genevese Aquifer convention, all agreements for specific aquifers were preceded by large externally funded projects which had a substantial component of knowledge generation and study of the shared resource and which aimed at data and information collection and exchange.

Guidance from global and regional legal frameworks. Where no treaty exists for an aquifer, regional and global legal frameworks, most importantly the Draft Articles on the Law of Transboundary Aquifers, frame states' rights and obligations with respect to shared groundwater resources. They are of a very general nature and need to be applied to the specific local context.

Prospects

A wide range of developments will require new or better legal responses. At the domestic plane the assumption that permit systems are invariably the best way forward to address issues of groundwater scarcity and degradation is increasingly being challenged and other and more creative approaches are called for to get a handle on the *de facto* open access nature of groundwater in many countries. In terms of substance, environmental concerns are likely to take a more and more prominent role in groundwater legislation, something that could already be observed with respect to water law in general over recent decades and which is borne out particularly well in the legal developments in Europe. The effects of climate change will require exploring what role the law will be able to play in enhancing adaption strategies and mitigation actions. The discussion about the right to water might lead to water policy and legislation being increasingly measured against human rights criteria, particularly with respect to non-discrimination and small-scale uses. Finally, the growing use of the subsurface by tapping deep seated aquifers, developing geothermal energy, hazardous waste disposal, storage and recovery of substances and heat, and accommodating technical infrastructure, is likely to result in requirements for new legal rules, domestic as well as international as far as transboundary aquifers are implicated.

At the international plane, growing pressure on groundwater resources might lead to more cooperation with respect to specific transboundary aquifers. It may take a number of forms from informal cooperative approaches to joint activities following the adoption of a fully fledged treaty. Timely cooperation will offer opportunities to mitigate harm early and to avoid crisis situations. Developing countries are likely to require donor assistance when embarking upon such endeavours. At the global level, the Draft Articles on the Law of Transboundary Aquifers might in time lead to the adoption of a framework convention on transboundary aquifers, which will be discussed in the UN General Assembly at the end of 2013.

Thematic Paper 6

Legal and Institutional Frameworks

By

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TABLE OF CONTENTS

Acknowledgements

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1. Introduction

Legal frameworks play a crucial role for effective groundwater governance. They provide the basis and starting point for policy development and they turn policy decisions into rights and obligations. The legal framework for groundwater management should provide answers to key questions such as who can access groundwater, where, for which purposes and under which conditions? How are aquifers protected against depletion and pollution? According to which criteria are the finite resources of non-recharging aquifers to be allocated and protected? Which kind of monitoring and planning tools have to be used? How will private and public interest be balanced and how get stakeholders involved in decision making and management processes?

Box 1: A working definition of groundwater governance

Groundwater governance is the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck, 2007. Dictionary and Introduction to Global Environmental Governance)

Historically water legislation has focused on surface water resources, among other reasons because the state of groundwater is unseen, the resource is ubiquitous and aquifer systems respond over time creating less immediate regulatory pressures. Groundwater legislation has lagged behind. In many countries it remains fragmented, incoherent or simply ignored. Over the last decades, increasing pollution of aquifers and large-scale and intensive abstraction of groundwater caused by the advent of the energized pump have created a need for better legal responses. Specific groundwater legislation has been enacted or provisions on groundwater have been formulated in general water legislation. As for surface water the introduction of modern water legislation with permit-based systems of administrative water rights at their core has become the dominant legal paradigm for groundwater.

In countries with highly formalized water economies such as Australia, many European countries or the US such legislation tends to reach most or all groundwater users. In many developing countries it has remained ineffective. There, the implementation of groundwater legislation is even patchier as of surface water rules and can constitute a paramount administrative challenge. Typically large numbers of small-scale users individually abstract marginal amounts which collectively generate significant impacts on aquifers.[1] Particularly in the rural areas of developing countries informal or customary rules tend to govern access to groundwater at the point of abstraction and shape users' perceptions of their rights, instead of or in parallel to formal water rights. Limited information about the characteristics of aquifers and use patterns as well as weak institutional capacity further complicate management processes. In such contexts user-based community approaches, the recognition of customary rules or a combination of options are highly relevant.

Whereas day to day management of groundwater resources takes place within the national sphere, and often at local level, domestic regulatory systems cannot be seen in isolation from international legal frameworks when transboundary aquifers are concerned. In that case international law determines states' rights and obligations to which domestic law has to be made compatible. Given that there are at least 273 transboundary aquifers worldwide this is a frequent constellation (UNESCO, 2009). However, at the international plane, both regulation and implementation are at an even more nascent stage than domestically: While for the 263 river basins hundreds of treaties have been concluded, only five of the 273 transboundary aquifers are covered by specific agreements and no regional or global treaty exists on transboundary aquifers (Mechlem, 2011). Guidance is provided mainly by isolated provisions on groundwater in surface water treaties and by non-binding legal instruments. Among the latter, the International Law Commission's 2008 Draft Articles on the Law of Transboundary Aquifers stand out. They were taken note of by the United Nations General Assembly and might

[1] In India there are, for instance, 19 million mechanized wells and tubewells (in 2000), Shah et al., 2003.

become the basis of a future convention (Resolutions 63/124 of 11 December 2008 and 66/104 of 9 December 2011).

The discussion will develop as follows: Part 1 (Baseline) will provide an overview of the main features of legal and institutional frameworks on groundwater first with respect to domestic law, addressing both formal and customary approaches, then with respect to international law. Part 2 (Diagnostic) will discuss key challenges that have to be addressed if legal rules are to make a more effective contribution to getting a handle on aquifer depletion and degradation – again both with respect to the domestic and the international plane. Part III (Prospects) will look into the future and suggest issues whose relevance is likely to increase. The legal issues covered here focus on the use of groundwater for human consumption, agricultural, industrial and environmental purposes. They do not address the legal challenges arising from newer technologies such as those related to the use of geothermal energy, carbon dioxide capture and storage (CCS), and hydrofracturing ("fracking") to capture shale gas, where in many cases specialized laws and regulations still have to catch up with technological developments (van der Gun, A. Merla, M. Jones and J. Burke, 2012).

Part 1 Baseline

2. National legal and institutional frameworks

2.1 Water law and its context

Rules on water exist in a number of forms ranging from informal local arrangements to administrative rights created by legislation. Contemporary criteria against which water rules are measured include whether mechanisms created are accountable, transparent and participatory, and whether they deal with water resources in an integrated manner and enable sustainable management of renewable water resources.

Formal water law is part of a country's natural resources and environmental legislation. Surface and groundwater are dealt with in a single water law or in two or more pieces of legislation, including laws and regulations, sometimes in a piecemeal fashion. Recently a trend has developed to address both resources in one water law complemented by subsidiary legislation (orders, decrees, regulations and the like), whereas historically surface and groundwater have often been addressed by different laws and regulations, compromising an integrated approach and posing greater challenges with respect to coherence and consistency. In federal states the management of water resources may be fully or partly attributed to individual states resulting in a legal framework that is not uniform nationwide. This is the case for instance in Germany, India and the US. In India the federal government has tried to influence state legislation by circulating a model groundwater bill ("Model Bill to Regulate and Control the Development of Groundwater", 1970, revised and re-circulated in 1992, 1996 and 2005) and over the last fifteen years a number of states have enacted legislation based on the model.

Box 2: Inter-state Agreements

Some federal states, notably Australia and the US, have concluded inter-state agreements for groundwater that span their internal boundaries. Examples are the Interagency Agreement in the Matter of the Coordinated Management of the Pullman-Moscow Ground Water Aquifer (Idaho – Washington, 1992) and the Border Groundwater Agreement (South Australia – Victoria, 1985, updated in 2005). Other agreements, sometimes also called compacts, make reference to groundwater. Interstate agreements are part of the body of national legal instruments.

Provisions on groundwater management are also contained in legislation relating to land-use planning, public works, agricultural development, the environment and mining, health and sanitary issues, among others. Land law, i.e. the law that deals with the rights to use, alienate or exclude others from land, is an area with important implications for access to groundwater and its protection and the land-water interface needs to be carefully managed (see 0).

In addition to formal legislation customary law and local rules play an important role in groundwater management, in particular in the rural areas of developing countries (see 0). Reconciling the need for formal water rights with customary traditions is one of the key challenges in groundwater governance. Legal and administrative rules set at the state level often coincide with detailed sets of informal or customary rules that govern water use and transactions at the point of abstraction.

Box 3: The right to water

The human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses (United Nations Committee on Economic, Social and Cultural Rights, General Comment No. 15). It has received further support when 122 countries formally recognized it in the United Nations General Assembly (Resolution (A/64/292) in 2010.

Among the different uses of water (human, agricultural, industrial, environmental) the right of humans (and sometimes domestic animals, particularly in Africa) to quench their thirst enjoys universal priority, often together with other basic domestic needs. This approach is in line with the human right to water (see United Nations, Committee on Economic, Social and Cultural Rights, General Comment No. 15, 2003).

2.2 Ownership and control

Historically as regards the use of groundwater specific rights were often conferred on the owner of the overlying land. Four doctrines have been widely applied in western or western-influenced systems: absolute ownership, reasonable use, correlative rights or prior appropriation (Caponera, 2007; Burchi and Nanni, 2003). In Islamic law there is no right of ownership on groundwater, which is considered to be a public good, but the ownership of a well entails ownership of a certain amount of adjacent land called *harim* or forbidden area. It varies in size according to different schools (Caponera, 2007). Customary regimes in many parts of the world view groundwater resources as belonging to the community and reject the concept of individual rights over water.

While rules granting strong private rights on landowners still exist in some parts of the world such as Texas ("rule of capture") or parts of India, there is worldwide a predominant trend to make access to the use of groundwater independent of the regime of the overlying land and to vest ownership of or control over all water resources in the state or to recognize the state's superior right to the management of water resources (Burchi and Nanni, 2003). The state becomes the guardian or trustee of groundwater resources. This step changes the status of groundwater from a private to a public good. The former owner becomes a user who must apply for a permit to obtain a right to abstract water, i.e. there is a formal separation between the two concepts of "ownership" and "right to use". This is the first step of introducing a system of formal water rights that allows the government to manage and protect groundwater resources in the interest of the public.

2.3 Formal water rights systems

The next sections will discuss the central elements of a formal water rights system. Worldwide there is a clear trend to try to formalize the water sector by introducing administrative water rights. Whereas such systems work well in Australia, Canada, Europe and the US, they often fail to deliver in countries where the water sector is less formalized or even predominantly informal as in Sub-Saharan Africa.

2.3.1 Regulating drilling and drillers

Borehole digging or drilling and well construction for exploration and exploitation tend to require prior notification, a permit or registration, for instance in countries as diverse as Kenya, the Northern Territory of Australia, Oman and the Philippines, to protect groundwater, to retain control of and information over access to it and to prevent conflict among users. Obligations to sample and to file drilling reports ensure that drillers supply groundwater data to the administration (Nanni et al., 2006). Drilling fees may be imposed.

In view of the skills required, legislation may subject the exercise of the profession of commercial well digging or drilling to registration or licensing requirements to ensure that the person of the driller is appropriately qualified and that borehole construction standards are maintained (Burchi and D'Andrea, 2003). In many cases, however, the drilling industry is not regulated and opportunities for getting away with poor constructions standards abound (GEF, 2012).

2.3.2 Protecting groundwater quantity

The central element of most current water laws is the tool of water rights as the standard approach to controlling demand. The granting and denial of water rights enables the water administration to allocate water to different uses ranging from domestic, agricultural and industrial uses to environmental ones such as sustaining wetlands and the baseflow of rivers. Permit-based systems have gained prominence in particular since more powerful pumps, population growth and economic development have driven demand for groundwater, often in excess of supply.

Under a system of water rights a permit has to be acquired by a user before (ground-)water can legally be abstracted.[2] This obligation is incumbent upon whoever the user is, including state agencies such as those involved in the development of irrigation schemes. Small-scale or *de minimis* uses are typically exempt. Permits are typically granted for a renewable time period, which is short enough to provide the state flexibility in the resource management, on the one hand, and a stable basis for the user for planning and investment decisions, on the other hand. The length of this time period varies considerably and depends on local context, the purpose of abstraction and the state of the aquifer. Permits provide for annual or seasonal volumetric allocations or are based on an area quota. They also state the purpose for which the water may be used, water protection measures to be taken and the obligation to pay fees or charges, among other things (on fees and charges see 0). Permits require that use be made of the water right failing which the right will lapse.[3] The metering of wells is often imposed in order to verify compliance with the conditions attached to a permit and to measure the amount of water abstracted. Where the transaction costs of metering would be too high, estimates are sometimes used. Permit holders have the obligation to report regularly (normally on an annual basis) how much water has been abstracted. Permits are usually recorded in a registry which serves as a tool for planning purposes.

In some instances, legislation determines the overall amount of permitted withdrawals per year. An example is the Edwards Aquifer Authority Act (Texas) which precludes the Edwards Aquifer Authority from authorizing withdrawals from the entire aquifer exceeding 572,000 acre-feet (approximately 705,550 cubic meters) of water annually (Edwards Aquifer Authority Act, 1993). The Namibian Water Resources Management Act empowers the Namibian Water Minister to determine the safe yield of aquifers for the purpose of guiding determinations concerning the abstraction and use of water from the aquifer. “Safe yield” is defined as the amount of water which may be abstracted from an aquifer at a rate that will not reduce the supply to such an extent as would render such abstraction harmful to the aquifer, quality of the water or environment (Water Resources Management Act No. 24 of 2004, Namibia, section 51).

In some countries – Australia, Chile and the US – groundwater abstraction permits may be traded, subject to some form of prior involvement of the water administration to protect both private and public interests and to mitigate negative impacts of such trades (Solanes, 1999).[4] Other countries, especially in South Asia, have informal water trading schemes.

Administrating a permit system is a costly, administratively challenging and time-consuming process – and one which has failed where its introduction was not well designed and tailored to the local context and administrative capacity. Due to considerations of cost and administrative convenience small-scale or *de minimis* uses, which are particularly important in developing countries, usually do not require a permit. Widely accepted *de minimis* uses include the use of water for drinking, watering domestic animals and poultry, recreational uses, such as bathing, meeting of basic household needs, the watering of garden plots and fire fighting (FAO, forthcoming). Defining *de minimis* uses is a tricky task that requires taking into account local circumstances (see 0).

Groundwater quantity is also influenced by artificial recharge which may be used as a tool for recovering water levels. Water legislation may provide for artificial recharge with surface water, stormwater or wastewater. In this case, the legislation will require that certain conditions as to the qualifications of the operators in the sector and to water quality are met. Operators will have to register with the water administration and the process will be subject to a permit (Nanni *et al.,* 2006).

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[2] In this paper the terms permit, license, authorization etc. are used interchangeably.

[3] Another mechanism to promote use of a water right was chosen by Chile. Under the 1981 Water Code a water right had to be issued against no payment once a person applied for it provided that water was available and that third parties did not suffer prejudice. The Code was amended by Law No. 20.017 of 11 May 2005, which, among other, introduced a tax for non-use (*patente por no uso*) to be paid by those holding a water right but not using the water. The tax rate increases depending on the length of time of non-use and on the place in which the water should have been used. In the case of non-payment, the water right is revoked. This aims at preventing powerful enterprises from hoarding water to reserve for future or, or to speculate on it in times of shortage through market mechanisms.

[4] It should be noted that the use of cap and trade schemes to address environmental problems is on the rise. Climate change in particular is the prime example of a field in which States have decided to rely on the market to address an environmental problem.

2.3.3 *Protecting groundwater quality*

Groundwater quality protection is the second main goal of legal frameworks for groundwater and the one that poses more intractable challenges than getting a handle on abstractions.

Groundwater pollution and degradation, which is sometimes irreversible, is caused by a plethora of activities and a much wider set of actors than groundwater abstractors. Drilling and pumping mobilize naturally occurring pollutants such as arsenic or fluoride or induce saline intrusion. For instance, in many small island states such as The Bahamas and Barbados salinization from overpumping of aquifers and thus salinity intrusion into the islands' underlying freshwater lens is a matter of great concern (IPPC, 2001). All poor quality wastewater generated on the land surface will find a pathway into an aquifer.

The activities causing pollution are broadly grouped into two categories, each triggering distinct legal answers. Point sources of pollution relate to pollution whose entry point into an aquifer can be established with sufficient certainty such as landfills, waste dumps and the underground storage of substances. In contrast, non-point source pollution originates from diffuse or indistinct sources whose origins, entry point into groundwater and impact are difficult or impossible to determine with accuracy. The prime example is agricultural runoff but also stormwater runoff in urban areas plays a role.

Legislative provisions on the protection of groundwater from pollution tend to be scattered among a variety of legal texts, including general environmental protection legislation. Their goal is to prevent, abate and control pollution with a view to achieving public health, social, economic and increasingly environmental objectives such as minimizing harm to dependent ecosystems. A number of instruments are used to achieve these goals, including the setting of water quality targets in relation to various water uses, the classification of water bodies into categories, and reducing and regulating abstraction. Point-source pollution is addressed by absolute prohibitions or limitations on emitting certain substances and lists of substances may be established the introduction of which into groundwater is prohibited, limited, investigated or monitored. Polluting activities may be permitted subject to wastewater discharge permits, often subject to prior treatment requirements and compliance with effluent standards (Caponera, 2007). For the members of the European Union (and for accession countries) the EU Water Framework Directive provides a particularly stringent system of groundwater quality protection.

Non-point source pollution measures include the regulation of land uses giving rise to diffuse discharge (see 0) and the imposition of best management practices. The identification of those who cause groundwater pollution may be problematic. The whole array of actors involved in land-use and pollution management, including urban water supply utility managers and agricultural and environmental agencies seeking to regulate the application of fertilizers (e.g. nitrates) and pesticides have to be involved in groundwater quality protection and addressed by legislation.

As an accompanying measure serious groundwater pollution can be treated as a criminal law offence which is punishable with higher penalties than mere civil or administrative offences. Due to the complexities of groundwater flow and the time lag between the occurrence of pollution and the moment its effects are felt, it is often technically difficult to prove liability for pollution (Caponera, 2007).

Modern technologies allow using the subsurface for a range of newer activities which may contaminate groundwater. Among them are the storage of hazardous waste such as nuclear waste, nuclear testing, the injection of fluids for soluble mineral extraction, the storage and recovery of heat and hydrocarbons, carbon capture and sequestration (CCS), hydraulic fracturing ('fracking') and the injection of residual geothermal fluids (on the risks of shale gas drilling for groundwater, see EPA, 2011). These activities require specialized laws and regulations which overall still need to catch up with technological developments.

2.3.4 *Economic mechanisms and environmental law tools*

Economic mechanisms and general environmental law principles and tools play an increasingly important role in regulating groundwater law.

Resource abstraction fees as a direct pricing mechanism make a contribution to groundwater governance by trying to influence demand. They are broadly related to the "user pays" principle. Charges may be calculated on the basis of a number of different criteria including the volume of water abstracted or the area in which it is used, the kind of use to which the water is put, the type of source from which the water is abstracted or the costs of their administration. Charges may increase progressively with the volume abstracted. Non-payment may lead to the suspension or even the loss of the right. It is common for payments in arrears to be liens on the property benefitting from a water right. It is also usual that debts be collected through the procedures applied for the collection of taxes in arrears (FAO, forthcoming). Where groundwater can be abstracted for free no incentive to reduce use is provided. For producers water becomes an input at zero cost despite the substantial costs of its use for society. Consequences are inefficient groundwater use, sometimes even further promoted by subsidized energy rates as in the case of agricultural water use in India or Malta (Garduño *et al.,* 2011; Malta Resources Authority, 2004).

Indirect pricing incentives such as increasing energy tariffs are other measures of demand management. The goal should be to devise a system of pricing that aligns the incentives for groundwater use with the goal of sustainability without harming poor small-scale users. Policy measures such as incentives to change production patterns and subsidies for efficient use such as irrigation systems may play a further role (GEF, 2012). Charging for wastewater discharge permits incorporates the “polluter pays” principle and is used to create an economic incentive to protect groundwater resources from pollution.

Also other environmental tools play an increasingly prominent role in water legislation. These include environmental criteria for water permits, pollution prevention and abatement standards (see 0), environmental impact assessment requirements, the relative prioritization of water allocations for environmental purposes, groundwater exploitation controls for ensuring the viability of dependant ecosystems, protected areas, and general environmental perspectives in the water legislation (Eckstein, 2010).

The obligation to carry out environmental impact assessments is becoming a prerequisite for the granting of abstraction or discharge permits above a certain quantity of water or before allowing projects of industrial, agricultural or other type with potentially negative impact on aquifers. Provisions on environmental impact assessments can be found, for instance in the water legislation of a large number of countries among them as diverse jurisdictions as Cameroon, Mexico, Kenya and Paraguay (Eckstein, 2010). The allocation of water to an “environmental reserve” as in South Africa aims at promoting sustainable use of water resources and preserving dependent ecosystems such as wetlands. Finally, environmental objectives in legislation support the allocation of groundwater to groundwater dependent ecosystems and the baseflow of rivers.

2.4 Monitoring

Groundwater quantity and quality monitoring provides the basis for planning, allocation and conservation decisions.

Information from modeling and monitoring enables scientifically based management decisions to ensure that in case of aquifers under pressure water remains safe and water rights secure and not threatened by falling water tables putting water out of reach or deteriorating quality attributes. Once baseline data of the characteristics of an aquifer system is available regular monitoring of changes in flow, storage and water quality informs about the impact of abstraction and pollution activities. Together with inventories of wells (sometimes limited to certain locations or to wells showing specific characteristics) and registers of abstraction and wastewater discharge permits, the data made available through monitoring enables the water administration to recognize critical situations and to intervene accordingly. Monitoring also helps to establish liability, for instance for polluting incidents, although the concealed and inaccessible nature of groundwater and the slow changes in quantity and quality cause difficulties in practice.

The main piece of water legislation usually contains obligations to monitor groundwater use and status while detailed parameters are often contained in subsidiary legislation or technical guidelines. Legislation may (and should) also require groundwater-related institutions to coordinate data-gathering, interpretation and storing. Monitoring by the water administration is complemented by information provided by well owners on their abstractions.

Monitoring aquifers is a technically demanding and costly exercise so that information about many aquifers is very incomplete. The costs for setting up a monitoring network, collecting data regularly, processing, interpreting and storing it in databases, including unified databases at the national level, are one of the reasons why in developing countries water rights and monitoring obligations, especially with respect to groundwater, remain unimplemented.

2.5 Planning

Although some degree of uncertainty is no impediment to planning, scientific research and the information gathered by data collection provide the basis for the preparation and periodic revision of water resources management plans which are required by legislation, for instance, in Morocco, South Africa, Uganda, South Australia and Texas and by the European Water Framework Directive (Hodgson, 2006). Water management plans may have a legally binding nature and are developed to promote rational, effective and fair water management and decision-making.

Depending on the hydrogeological setting, the degree of surface-groundwater linkage, the significance of the aquifer and the limitations of the legal and institutional framework in place different types of plans have proved to be useful. For significant aquifers or fossil aquifers management plans can be developed which can be complementary to integrated water resource planning at the national level. Alternatively, as all recharging aquifers occur within river basin management units, groundwater can be integrated into river basin planning, which, however, often faces a range of constraints and might be premature for some countries (Garduño *el al.,* 2006). An example of the former option is the Groundwater Management Plan for the important Edwards Aquifer in Texas, which guides the activities of the Edwards Aquifer Authority.

Where the water legislation does not establish development and management priorities, such may be included in a management plan. In addition, management plans typically contain the characteristics of a river basin or aquifer, a review of the impact of human activity, objectives with respect to quantity and quality of the resource and measures to meet the objectives. In the case of non-renewable aquifers or of aquifers for which a policy choice in favour of mining has been made the plan may need to address depletion. Typically a range of stakeholders is involved in plan preparation and revision (see 0). Participation in planning processes under the EU Water Framework Directive is a case in point: Under Art. 14 of the EU Water Framework Directive Member States shall encourage the active involvement of all interested parties in the implementation of the EU Water Framework Directive and in particular in the production, review and updating of river basin management plans which are mandatory for all basins under the directive. Where groundwater does not follow a particular river basin it is assigned to the nearest or most appropriate river basin (Article 3 EU Water Framework Directive).

2.6 Customary and community-based approaches

In many jurisdictions formal law does not exist or, particularly in Africa, the formal law may recognize specified areas as being subject to customary rules. Customary law or informal arrangements may also be the de facto dominant legal paradigm despite formal law being in place. The latter may be rejected or simply not be implemented and thereby replaced by other rules. The relationship between customary and formal law invariably tends to be complicated and unclear.

Customary water law practices and rights and informal arrangements hold sway in much of the rural areas of the developing world. They govern the use of water by large proportions, if not the majority of the world's citizen's (van Koppen *et al.,* 2007). Community-based water law is often but not necessarily local. It may cross even international boundaries as the example of pastoralists in sub-Saharan Africa shows whose water use agreements with each other and settled farmers cover large areas.

Customary water law regimes are often complicated. Water tenure may form part of a broader customary legal framework that regulates access to other natural resources such as land and forest. Different customary law regimes or customary rules may only apply within particular societies or groups such as pastoralists. Within a national context a range of diverse and heterogeneous customary rules may exist and conflict may arise between users of water under different customary tenure arrangements (e.g. between pastoralists and settled farmers).

Also, the extent of water resources may exceed the territorial application of local rules (FAO, forthcoming). Groups or communities rather than individual users have rights. All these factors pose challenges when attempts are made to align customary and formal law. As most customary uses are also *de minimis* uses the challenges posed by the latter also apply to most customary uses (see 0).

Many countries have attempted to replace customary and community-based rules with a formal administrative rights based permit system, often with only limited success. Research has shown that the extent to which water policy, law and administration are able to bring into their ambit all or most water transactions depends on the degree of formalization of the water economy which is in turn determined by the overall development of the national economy (Shah, 2007). In developing countries the water sector is predominantly informal and although water legislation may exist it is often implemented only in urban areas and rapidly industrializing regions. In such contexts customary, local and informal approaches dominate.

The penetration of the state to the local level varies around the world. In places like China there is substantially more connection between local and national political bodies than elsewhere (van Koppen *et al.,* 2007). In sub-Saharan Africa traditional tribal authorities command land, water and other natural resources and exist often side by side with the elected local government (van Koppen *et al.,* 2007). Research on India has revealed that most users rely on self-provision of water (through private wells, streams, ponds), on local, informal exchange institutions and on community-managed water sources (Shah, 2007). In many contexts attempts to enforce a modern permit-based water law may thus prove very difficult and not the most suitable way forward. Alternative as well as supplementary approaches might have to be considered (see 0 and 0).

2.7 Institutional aspects

Institutional set-ups to manage aquifers and to administer water rights vary highly across countries. In most countries a plethora of multi-level water resources administration institutions tends to exist. A systematic discussion of such institutions according to their powers, functions, uses, territorial level of jurisdiction or legal regime is beyond the scope of this thematic paper.[5] As intensive development of groundwater is recent, institutional responses tend to lag behind the tasks created by new legislation. Traditionally, geological surveys or agencies have informed water resource and environmental regulators. Only a few countries have attempted to set up dedicated groundwater management agencies such as India with the Central Groundwater Authority and the Central Groundwater Board (Garduño, 2011). In federal countries federal, state and local institutions may be vested with functions and powers in respect of groundwater.

The highest and ultimate responsibility for water management is often conferred upon one or more ministers, usually acting through a statutory Director or Director-General of water resources, such as the Department of Water Affairs and Forestry in South Africa, or some other statutory body such as an authority (e.g., the Jamaica Water Authority) or agency (e.g., the Environment Agency in England) or Directorate of Waters (e.g., the *Direccción General de Aguas* in Chile) (Hodgson, 2006). Ideally, the entire range of groundwater management issues would be placed in the hands of a single water resources institution, which would also be in charge of surface water (Nanni *et al.,* 2006). This is, however, the exception rather than the rule. An interministerial/interagency mechanism such as a council, commission or committee usually has the task of coordinating those ministries and agencies that also have a stake in aquifer management (Nanni *et al.,* 2006).

There is an increasing trend to complement the water resources institution which bears overall responsibility throughout the jurisdiction with coordinating/decision-making institutions at the drainage basin level. Groundwater management is either included in the scope of institutions set up at the river basin, even where

[5] For such an analysis of national water resources administration institutions see Caponera, 2007.

aquifer boundaries do not follow the boundaries of the river basin[6] or, still more rarely, a mechanism is set up specifically at the aquifer level.[7]

The main tasks of a water authority comprise planning and modelling future demands and impacts on water resources, organizing stakeholder fora, monitoring of water quality and quantity, issuing and administrating water rights, including the maintenance of registers, and implementing and enforcing the water law and water rights regimes, e.g. by meting out administrative fines in cases of non-respect for legal obligations or the terms and conditions of a permit (FAO, forthcoming; Hodgson, 2006). Water authorities often fall short of delivery on these tasks due to institutional weaknesses, lack of empowerment, gaps in mandate and a number of other factors. For instance, the countries of the former Soviet Union only gradually introduce resources monitoring reflecting the principles enshrined in the EU Water Framework Directive. Institutional deficits inevitably result in implementation deficits which erode the contribution a legal framework can make to aquifer governance (see 0).

In federal countries large aquifers spanning several states may call for inter-state institutional mechanisms. This is the case of the Great Artesian Basin (GAB) shared by Queensland, New South Wales, South Australia and the Northern Territory, one of the largest basins in the world covering 22 percent of Australia, for which the Great Artesian Basin (GAB) Consultative Council has been established (Caponera, 2007, 98).

[6] For instance Art. 3 of the EU Water Framework Directive requires that where groundwaters do not fully follow a particular river basin, they shall be identified and assigned to the nearest or most appropriate river basin district.

[7] See also Article VI(2) of the UN ECE Groundwater Management Charter which states that ''the territorial competence of [water authorities or co-coordinating bodies] with respect to groundwater management should not necessarily be limited to . . . catchment areas, but should allow for encompassing, as appropriate, management of aquifers in their entirety.''

3. International legal and institutional frameworks for transboundary aquifers

3.1 Agreements for specific transboundary aquifers

Only five agreements have been concluded for specific transboundary aquifers (Mechlem, 2011). These are the Genevese Aquifer, the Nubian Sandstone Aquifer, the North Western Sahara Aquifer, the Iullemeden Aquifer and the Guaraní Aquifer. In other international treaties groundwater is addressed among other issues or as a side aspect of surface water management.

In 1977 the first aquifer specific agreement was concluded between two local authorities, the Franco-Swiss Arrangement on the Genevese Aquifer.[8] It covers a relatively small local aquifer of only 19 km in length and 1–3 km in width whose characteristics were well known compared with what is known about most other transboundary systems, especially in developing countries (Walter, forthcoming). The Arrangement was concluded to address a clearly defined problem, namely over-pumping resulting in falling water tables. Under the Arrangement the Swiss constructed and have operated an artificial recharge installation. Both parties agreed to share the costs of construction and operation. A management commission was created that proposes yearly aquifer utilization programmes to ensure that abstraction is matched by sufficient artificial recharge. The French were allowed to abstract up to 5 million m^3 per year of which 2 million m^3 are free of charge.[9] This is the only specific allocation clause in any of the few aquifer agreements. The Arrangement is devoid of any abstract principles and of a highly technical nature. In 2008, when it expired, it was replaced by a Convention.[10] The agreement on the Genevese Aquifer was an exception at the time and its successor convention has remained so in many respects. They stand out because of the level of detail they provide, the degree of joint management of the shared aquifer, the active commission and the tangible impact they have had on the sound management of the aquifer.

In 1992, a joint authority for the study and development of the Nubian Sandstone Aquifer System was created to enhance cooperation in managing the aquifer system's water resources.[11] In 2000, the Nubian Sandstone Aquifer System States concluded two further short and limited agreements.[12] The first is on monitoring and exchange of groundwater information. It foresees the sharing of data consolidated during an international externally funded programme for a regional strategy on the aquifer and included in an information system, the Nubian Aquifer Regional Information System (NARIS). The second agreement is on monitoring and data sharing. It establishes obligations of continuous monitoring of the aquifer and sets out detailed parameters of the aquifer to be monitored, including yearly extractions, number of wells, electrical conductivity measurements and water levels. Together the three agreements provide a legal framework for data and information exchange as a step towards sustainable management of the Nubian Sandstone Aquifer System.

Cooperation efforts are also ongoing with respect to the North-Western Sahara Aquifer System, better known by its French acronym SASS, which is shared by Algeria, Libya and Tunisia and extends across more than 1 million km^2. A short and bare-bones agreement established a technical consultation structure at the end of 2002, which

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[8] *Arrangement relatif a la protection, a l'utilisation et a la realimentation de la nappe souterraine francosuisse du Genevois, Geneva, 9 Juin 1977, Le Conseil d'Etat de la République et Canton de Geneve-Préfet de Haute-Savoie*, original text and unofficial English translation available at: http://internationalwaterlaw.org/documents/europe.html#European Aquifers.

[9] This limitation of the French use is balanced by the fact the installation is owned by the Swiss and that the Swiss are responsible for its construction and operation (Wohlwend, 2002).

[10] *Convention relative a la protection, a l'utilisation, a la realimentation et au suivi de la Nappe Souterraine Franco-Suisse du Genevois*, 18 Décembre 2007, La Communauté d'Agglomération de la Région Annemassienne, la Communauté de Communes du Genevois, la Communauté de Viry-République et canton de Genève, available at: http://www.internationalwaterlaw.org/documents/regionaldocs/2008 Franko-Swiss-Aquifer.pdf.

[11] Constitution of the Joint Authority for the Study and Development of the Nubian Sandstone Aquifer Waters, reproduced in http://www-naweb.iaea.org/napc/ih/documents/Nubian/Nubian_final_MSP_ Sandstone.pdf (Annex 7). It was established first by Egypt and Libya. Sudan and Chad became members subsequently.

[12] Reprinted in Burchi and Mechlem (eds.), 2005.

became a standing consultation mechanism in 2007 hosted by the *Observatoire du Sahara et du Sahel* in Tunis (Reprinted in Burchi and Mechlem (eds.), 2005). Its objective is to coordinate, promote and facilitate the rational management of the SASS aquifers water resources. Its main functions are to manage a hydrogeological database and simulation model, to develop a reference observation network, to process, analyse and validate data and information about the aquifer and its use, and develop indicators on the aquifer and its use. Like the Nubian Sandstone Aquifer agreements the SASS agreement is silent on general principles and reflects a rather cautious and reserved approach to cooperation. In contrast to the Nubian Aquifer Sandstone System case effective cooperation has been initiated with respect to the joint data base and joint model.

In 2009 the three states sharing principally the Iullemeden Aquifer System, which covers 500 000 km^2, Niger, Nigeria and Mali, signed a Memorandum of Understanding relating to the Setting up of a Consultative Mechanism (on file with author, not yet in force). Its objective is to promote integrated management of the aquifer, cooperation and joint identification and management of risks as well as sustainable development. Among the 14 functions of the consultative mechanism are to provide opinions on policies and projects, to coordinate programmes, to make recommendations to harmonize legislation and to settle disputes. The parties also commit to take into consideration a range of general principles relating to equitable and reasonable utilization, public participation, non-detrimental use, precautionary measures, the polluter pays and the user pays principles. A chapter on general obligations emphasizes sustainability and protection of the aquifer. A chapter on planned measures sets out procedural obligations, including obligations to exchange data and information, and a detailed notification procedure. Finally provision is made for dispute settlement. The Iullemeden Memorandum of Understanding is the first comprehensive treaty for the management of a transboundary aquifer. It is very different in nature to the much more limited commitments made for the Nubian Sandstone Aquifer System and the SASS and the technical approach to the Genevese Aquifer and provides a basis for the joint management of the risks to which the shared aquifer is exposed.

Finally, in 2010 the Guaraní Aquifer System, with 1 200 000 km^2 one of the world's largest aquifer systems, located beneath Argentina, Brazil, Uruguay and Paraguay became the fifth aquifer for which an agreement was concluded, the Agreement on the Guaraní Aquifer (del Castillo Laborde, forthcoming; Sindico, 2011).[13] It is a framework agreement that emphasizes strongly the sovereignty of the states involved over their respective portions of the aquifer (on the issue of sovereignty see 0) and only subsequently mentions rational and sustainable use, the obligation not to cause significant harm, conservation and protection. It contains useful clauses on notification and exchange of technical information, cooperation, the identification of critical areas and dispute resolution. A commission is to be established under the La Plata River Treaty to coordinate cooperation. The Guaraní Aquifer Agreement is the first agreement that refers explicitly to the ILC Draft Articles on Transboundary Aquifers in its preamble (see 0). Its impact in practice will depend to a large extent on the role its commission will assume.

3.2 Groundwater in bi- and multilateral surface water treaties

Bilateral treaties that specifically address groundwater among other subject matters include the 1973 Agreement on a Permanent and Definitive Solution to the Salinity of the Colorado River (known as Minute No. 242),[14] which limits groundwater pumping by both Mexico and the United States close to the Arizona–Sonora boundary near San Luis. Other examples are the 1994 Israel–Jordan Peace Treaty[15] and the 1995 Israeli–Palestinian Interim Agreement.[16] The conventions on the Carpathians, the Danube, the Rhine and Lake Tanganyika as well as the Agreements on the Sava River Basin and on the Incomati and Maputo, and the Protocol for the Lake Victoria

[13] http://www.itamaraty.gov.br/sala-de-imprensa/notas-a-imprensa/acordo-sobre-o-aquifero-guarani; not yet in force.
[14] International Boundary and Water Commission United States and Mexico, Minute No. 242 of 30 August 1973, Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River, 12 I.L.M. 1105 (1973) (Minute No. 242).
[15] Treaty of Peace between the State of Israel and the Hashemite Kingdom of Jordan (Israel–Jordan Peace Treaty) Arava/Araba Crossing Point, 26 October 1994, 34 I.L.M. 43 (1995), Article 6 and 18 and Annexes II and IV.
[16] Israeli–Palestinian Interim Agreement on the West Bank and the Gaza Strip, Washington, DC, 28 September 1995, 36 I.L.M. 551 (1997), Annex III, Protocol Concerning Civil Affairs, Article 40, Principle 3(a) and (c).

Basin, inter alia, apply to surface as well as groundwater.[17] The mentioned treaties are generally based upon the areal limits of surface water management, primarily the river basin. The substantive provisions often reflect only negligible concern with groundwater. In other cases even the application of a treaty to groundwater remains open to interpretation, for instance, if a treaty refers to the "water resources" of a particular basin without defining any further its scope.

3.3 The regional level, especially the case of Europe

In Africa, the 2000 Revised SADC Revised Protocol on Shared Watercourses applies to groundwater associated to watercourses but suffers from the same shortcoming with respect to groundwater as the United Nations Convention on the Non-navigational Uses of International Watercourses (UN Watercourses Convention, see 0) on which it was modelled.[18] Also the African Convention on the Conservation of Nature and Natural Resources contains provisions on groundwater.[19]

The most advanced legal regime with respect to groundwater resources, transboundary and also domestic, exists in Europe. An earlier non-binding instrument is the 1989 UNECE Charter on Groundwater Management.[20] The 1992 UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention, "Helsinki Convention") covers, in contrast to the UN Watercourses Convention, all types of transboundary groundwater (1936 UNTS 269). The parties have an obligation to prevent, control and reduce transboundary impact and to take additional specific measures to prevent the pollution of groundwater. Furthermore, the Convention states that water-quality objectives and criteria shall take into account specific requirements regarding sensitive and specially protected waters and their environment such as groundwater resources. In 1999 the Protocol on Water and Health to the UNECE Water Convention was adopted to ensure the adequate supply of safe drinking water and adequate sanitation (2331 UNTS 202). It obliges parties, inter alia, to develop water-management plans on the basis of aquifers to promote the achievement of water quality targets and the protection of public health. It applies to transboundary and, remarkably, also to domestic groundwater resources. Starting from this legal basis currently model provisions on transboundary groundwater are being developed by the UNECE to enhance the organization's work these resources. In 2000, the UNECE also developed detailed Groundwater Monitoring Guidelines (UNECE Task Force on Monitoring and Assessment 2000).

For the members of the European Union (and candidate countries) the Water Framework Directive provides for a detailed, encompassing and ambitious regime of quantity and quality protection of all waters — rivers, lakes, coastal waters, and groundwater, domestic and transboundary — and sets the parameters for the water policy of each Member State.[21]

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[17] Framework Convention on the Protection and Sustainable Development of the Carpathians (Kiev, 22 May 2003), UN Doc. ECE/CEP/104; Convention on Cooperation for the Protection and Sustainable Use of the River Danube (Sofia, 29 June 1994), Official Journal of the European Union L 342, 12.12.1997, p. 19. Convention on the Protection of the Rhine (Berne, 12 April 1999), Official Journal of the European Union L 289, 16.11.2000, p. 31; Convention on the Sustainable Development of Lake Tanganyika (Dar es Salaam, 12 June 2003), http://faolex.fao.org/; Framework Agreement on the Sava River Basin (Kranjska Gora, 3 December 2002), http://faolex.fao.org/; Tripartite Interim Agreement Between the Republic of Mozambique, the Republic of South Africa and the Kingdom of Swaziland for Co-operation on the Protection and Sustainable Utilisation of the Water Resources of the Incomati and Maputo Watercourses (Johannesburg, 29 August 2002); http://faolex.fao.org/; Protocol for Sustainable Development of Lake Victoria Basin (Arusha, 29 November 2003), http://faolex.fao.org/.

[18] 2000 Revised SADC Revised Protocol on Shared Watercourses, 40 ILM 321 (2001); United Nations Convention on the Non-Navigational Uses of International Watercourses, annexed to UNGA Res. 229 of 21 May 1997, Official Records of the UNGA, 51st session, UN Doc. A/Res/51/229;also reprinted in 36 ILM 700 (1997

[19] http://faolex.fao.org/.

[20] Charter on Groundwater Management, adopted by the UN ECE at its forty-fourth session (1989) by Decision E (44), UN Doc. E/ECE/1197 ECE/ENVWA/12 [hereinafter Groundwater Management Charter].

[21] Directive 2000/60/EC of the European Parliament and of the Council of October 23, 2000 Establishing a Framework for Community Action in the Field of Water Policy.

Box 4 EU Directives
EU directives are supranational law which is unique in nature. Supranational law is neither international law, which is binding only between and among states, nor domestic law. EU directives are developed in legislative processes at the EU level but then have to be transposed into domestic law, i.e. the content of EU directives becomes part of the domestic legal system. In case members states fail to transpose EU directives the European Commission can initiate an infringement procedure before the European Court of Justice which may impose financial penalties. Under certain circumstances, EU directives may also be directly effective in member states' national legal orders.

The Water Framework Directive is based on the concept of integrated management of the water resources of a river basin. It provides for the recovery of costs, including environmental and resources costs, for water services in accordance with the polluter pays principle, and for public participation in water management. All waters in the European Union have to achieve 'good status' by 2015. 'Good groundwater status' is defined in terms of both quantity and chemical status. With regard to groundwater, the Water Framework Directive aims particularly to reduce significantly the pollution of groundwater. Member States have to prevent or limit the input of pollutants into groundwater, to prevent the deterioration of the status of all bodies of groundwater; and to protect, enhance, and restore groundwater. Direct discharges of all pollutants into groundwater are prohibited (to be made operational by 2012). To cover indirect discharges they have to monitor groundwater bodies so as to detect changes in chemical composition and to reverse any significant and sustained upward trend in the concentration of pollutants. With regard to quantity, Members have to ensure a balance between abstraction and recharge. They have to control and authorize all water abstractions as well as the artificial recharge or augmentation of groundwater bodies.

Currently the second main instrument on groundwater is a groundwater directive which is to be repealed in 2013.[22] It prohibits the direct discharge of certain toxic, persistent, and bioaccumable substances such as mercury or cadmium into groundwater and makes indirect discharges subject to prior authorization. The discharge of a number of other substances has also to be limited and be made subject to prior authorization. The current groundwater directive will be replaced fully by the Water Framework Directive and a daughter directive of the Water Framework Directive on groundwater quality.[23] The latter provides for criteria for the assessment of groundwater quality, for the identification and reversal of significant and sustained upward trends, and for the definition of starting points for trend reversals. It also complements the Water Framework Directive provisions on preventing or limiting inputs of pollutants into groundwater and aims to prevent the deterioration of all bodies of groundwater. The protection of groundwater has become a key concern and target in the EC context. The Water Framework Directive and its daughter directive provide the most advanced legal regime for domestic and transboundary groundwater resources. They have initiated an important process of improving the status of water resources within the EU. When assessing the success of the Water Framework Directive and evaluating the extent to which it can provide guidance to other regions, the unique legal nature of the EU, including its implementation and sanctions system, must be fully appreciated. It should also be noted that while environmental protection is now a self-standing goal of the EU, EU environmental law was initially based on economic considerations, namely on the idea of promoting comparable production conditions in the internal market by posing the same environmental obligations on each member.

3.4 The global level and the Draft Articles on the Law of Transboundary Aquifers

A binding legal instrument at the global level on shared groundwater resources is still outstanding. The most authoritative treaty on international water law, the 1997 United Nations Watercourses Convention[24] (not yet in force), formally applies to most shared aquifers but its provisions exclude certain types of aquifers, most

[22] Council Directive 80/68/EEC of 17 December 1979 on the Protection of Groundwater against Pollution Caused by Certain Dangerous Substances.
[23] Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the Protection of Groundwater against Pollution and Deterioration.
[24] United Nations Convention on the Non-Navigational Uses of International Watercourses, annexed to UNGA Res. 229 of 21 May 1997, Official Records of the UNGA, 51st session, UN Doc. A/Res/51/229; also reprinted in 36 ILM 700 (1997).

importantly non-recharging aquifers (Mechlem, 2003; Eckstein, 2005). In addition, its substantive provisions are exclusively geared towards surface water and completely ignore the specific management challenges posed by groundwater (Mechlem, 2003).[25]

Box 5 The International Law Commission
The International Law Commission is the body of the United Nations system mandated to codify and progressively develop international law. It is composed of 34 independent experts in international law. The International Law Commission has authored a number of documents central to international law today, a number of which have become international treaties.

Between 2002 and 2008 the International Law Commission developed a set of 19 draft articles on the law of transboundary aquifers.[26] The Draft Articles apply the general principles of international surface water law – equitable utilization, no significant harm and cooperation – to transboundary aquifers. They develop the content of these principles with respect to transboundary aquifers and add new (and partly controversial) issues like sovereignty. They also deal with protection, preservation and management, and procedural issues (Mechlem, 2009; Stephan, 2011). The United Nations General Assembly took note of the draft articles and encouraged States to make appropriate bilateral and regional aquifer arrangements taking them into account. Their final form, i.e. whether to take them as a basis of a convention on transboundary aquifers, will be discussed in 2013.[27] Although of a non-binding nature the draft articles are the most authoritative statement on the law of shared groundwater resources.[28]

Supplementary, sometimes detailed, guidance at the global level is provided by further non-binding instruments both of an official nature and developed by experts, starting with the 1977 Mar del Plata Action Plan that focused primarily on the utilization of aquifers and on increasing aquifer-related knowledge.[29] Fifteen years later, in 1992 the Dublin Statement and Chapter 18 of Agenda 21, in response to increasing water problems, emphasized sustainable use, integrated water resources management, and the protection of water resources and ecosystems.[30] This focus has been maintained in the 2002 Johannesburg Plan of Implementation.[31] The Conference of the Contracting Parties to the Convention on Wetlands of International Importance Especially as Waterfowl Habitat adopted in Resolution VIII.40 Guidelines for Rendering the Use of Groundwater Compatible with the Conservation of Wetlands.[32]

Among the non-binding instruments of experts in particular the 1989 Bellagio Draft Agreement Concerning the Use of Transboundary Groundwaters"[33] and the 2004 Berlin Rules on Water Resources of the International Law Association, which with respect to groundwater built on the earlier 1986 Seoul Rules of the International Law Association, are worth mentioning (ILA, 2004).

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[25] To fill the remaining legal gap the ILC adopted a Resolution on transboundary aquifers not related to surface water (called "confined transboundary groundwater"); ILC, Resolution on Confined Transboundary Groundwater, Art. 1, in Report of the Commission to the General Assembly on the work of its forty-sixth session, YBILC 1994, Vol. II (Part 2), p. 135 (ILC Resolution).
[26] United Nations General Assembly Resolution 63/124 of 11 December 2008, Annex.
[27] United Nations General Assembly Resolution 63/124 of 11 December 2008 and Resolution 66/104 of 9 December 2011.
[28] Their content is binding to the extent that it reflects customary international law.
[29] Report of the United Nations Water Conference, Mar del Plata, 14–25 March 1977, UN Doc. E/Conf.70/29. United Nations publication Sales No. E.77.II.A.12.
[30] Dublin Statement on Water and Sustainable Development of the International Conference on Water and the Environment: Development Issues for the 21st Century, 26-31 January 1992, Dublin, Ireland; Chapter 18 of Agenda 21 adopted at the United Nations Conference on Environment and Development, Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3-14 June 1992, UN Doc. A/Conf. 151/26/Rev.1, Volume 1, Annex II.
[31] Report of the World Summit on Sustainable Development, Johannesburg, 26 August – 2 September 2002, UN Doc. A/CONF.199/20.
[32] Resolution VIII.40 Guidelines for Rendering the Use of Groundwater Compatible with the Conservation of Wetlands adopted at the 8th Meeting of the Conference of the Contracting Parties, 18–26 November 2002.
[33] Reprinted and commented in R. D. Hayton and A. E. Utton, "Transboundary Groundwaters: The Bellagio Draft Treaty"(1989) 29 *Natural Resources Journal* 663.

A range of other international treaties has implications for aquifer governance, e.g., the United Nations Convention to Combat Desertification and the United Nations climate change regime. Under the latter carbon dioxide capture and storage in geological formations can be a project activity under the Clean Development Mechanism, one of the flexibility mechanism allowed in Article 12 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change.[34]

[34] United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa, 17 June 1994, 33 ILM 1328 (1994). Kyoto Protocol to the United Nations Framework Convention on Climate Change, 37 I.L.M. 22 (1998), 10 December 1997, U.N. Doc FCCC/CP/1997/7/Add.1.

Part 2 Diagnostic

4. Constraints and opportunities at the national level

Part I provided a snapshot of common approaches to regulating access and management of domestic groundwater resources and of legal initiatives taken with respect to transboundary aquifers. The experience of many countries shows that legislative frameworks for water often have less impact than desired on the *de facto* use and abuse of groundwater resources. Indeed, in many countries the potential of legislation to shape the governance of aquifers with a view to better use and protection of groundwater resources remains untapped due to a number of reasons. This section will discuss some of these reasons and suggest a number of challenges that have to be addressed if water legislation is to make a more meaningful contribution to improving groundwater governance.

4.1 Groundwater as a public good

Despite the trend to vest groundwater in the state groundwater continues to be perceived as an intensely "private" good in important countries. For instance, in Texas, the Indian state of Gujarat or the Pakistani Punjab the rule of capture is still dominant, allowing landowners to extract groundwater freely on their land (Burchi and Nanni, 2003).[35] As a result, regulation of access to and extraction of groundwater in the interest of the public is very weak in those countries.

More importantly, even where groundwater is formally a public good and users have only usufructuary rights, perceptions of it being "private" often linger on. They interfere with compliance with government regulation or generate transition problems from an unregulated to a regulated regime. The legal notion or the perception of groundwater being private property can be a strong driver for overexploitation. In order to ensure socially more equitable access to groundwater and sustainable management the link between land ownership and control over groundwater should be severed. To achieve changes of perception requires, however, legal as much as educational and awareness raising measures.

In some instances, changing the status of groundwater from a private to a public good has been challenged in courts of law on grounds of expropriation of constitutionally protected private property rights and compensation has been claimed. Such claims have usually been rejected on grounds that regulating groundwater abstraction arises from the need to safeguard the public interest (Burchi and Nanni, 2003).

4.2 Appropriate and coherent legal frameworks

In many jurisdictions groundwater is still regulated inadequately: the water legislation does not apply to groundwater, or does not address it in a technical and comprehensive manner, or is outdated, or contains gaps and inconsistencies.

A recent review of the water legislation of SADC member states revealed that almost all possess some form of water law but that many of these laws make no specific reference to groundwater (Vidal, 2010). In addition, inconsistencies between surface and groundwater law or between water, land and environmental law may undermine the effectiveness of legislation. For instance, if for surface water abstraction a permit is required but not for groundwater abstraction perverse incentives are created, i.e. the unintended consequence is that users will favour groundwater abstraction over surface water abstraction to avoid administrative hassle and fees.

In many situations introducing a new comprehensive law dealing with all water resources of a country in one piece, enshrining principles of integrated water management and creating secure water rights might seem like an attractive course of action to address such shortcomings. Introducing an implementable system of water rights, where such does not yet exist, yields a number of benefits provided that it is well tailored to the specific

[35] See also the recent (24 February 2012) *Edwards Aquifer Authority v. Day* Case ruling of the Texas Supreme Court.

local context. It allows managing water resources in a planned way that takes account of the needs of different sectors and the environment, recognizes the economic value of water, supports or entrenches wider economic reforms, promotes social goals and helps to ease pressure on aquifers (Hodgson, 2006). It also allows subjecting all water resources to a single regime in terms of both legislation and institutional arrangements for the implementation of such legislation, which is one element of an integrated water resources management approach.

Box 6 Integrated Water Resources Management (IWRM)
IWRM is a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership).

To introduce a system of formal water rights is, however, a complex task that may take years and is usually part of a more substantive water sector reform. It may fail if is not well designed, implemented and embedded in wider cross-sectoral policies or if it is not politically viable. In some contexts other approaches such as incorporating customary rules or relying more on community management than on permits alone stand higher chances of being successful.

Box 7 Malta
From the early 1980s an agrarian boom prompted by advances in drilling technology and sustained by EU-accession land-based subsidies resulted in deep boreholes unsustainably exploiting the sea-level aquifer and causing high levels of pollution. Despite strong pressures on the resource and EU Water Framework Directive obligations to achieve “good groundwater” status, attempts to introduce modern groundwater legislation within the framework of a larger water policy reform failed due to lack of interest on behalf of the government and the public as well as other political priorities (FAO, 2006).

Introducing a system of modern water rights requires careful managing of the transition process, involving stakeholders in designing the new regime and dealing with *de minimis* uses, customary rights and practices (see 0 and 0) and existing rights. Rights are typically granted to existing users on the basis of their declared historical use before new rights are allocated, whereas *de minimis* uses, defined according to local conditions, are exempt from permit requirements (Hodgson, 2006). Where existing uses are restricted issues of compensation may arise and be dealt with in legislation such as in Art. 22 (6) of the South African Water Act.[36] In legislative reform processes it may also be necessary to introduce amnesties on illegal boreholes in order to shed light on abstractions and to set the basis for acceptable solutions.

Staged approaches with respect to planning or the issuance of water rights for particularly stressed aquifers are an option provided that concerns over unequal treatment of different users can be addressed. Success depends both on the degree of acceptance of the new system and on the security of the rights provided; the latter in turn depends on the extent to which the law is implemented. To maintain or improve the quality of groundwater is usually a bigger challenge than getting a handle on quantity because a larger and more diverse group of actors is involved which has to be addressed by legal rules in primary and subsidiary water and related legislation.
In many situations it might be preferable for the sake of swift action to improve the implementation of existing legislation or to strengthen the capacity of existing institutions, e.g. by broadening their mandate and providing more staff, before embarking on lengthy new legislative projects.

4.3 De minimis abstractions

The degree of complexity of water legislation and in particular of a permit system must be commensurate with the available institutional, planning and administrative capacity. It must be carefully thought through where

[36] Republic of South Africa, National Water Act, Act No. 36 of 1998.

groundwater regulation should start and which uses should be excluded from permit requirements. For administrative convenience and cost it is standard practice to exclude small-scale users from permit requirements. Such *de minimis uses* can be defined with regard to volumes, or area, purpose and need to take into account local conditions. While for instance in the Murray–Darling basin small users are allowed to extract water for domestic or livestock needs, or for irrigating small plots of 2 ha or less, without a permit, the same rule would exempt over 95% of current groundwater irrigators if applied in South Asia or on the North China plains (Shah et al., 2003).

Exempting *de minimis* uses spares users the trouble and costs of obtaining a permit and the administration the burden of administrating them. The accumulated effects of such unregulated small-scale uses can generate significant negative environmental impacts where water demand outstrips supply. These can be felt both on groundwater through dropping water tables, eventual depletion, migration of low quality water or salinization in coastal areas and on springs, seepage zones and the baseflow of rivers. In terms of water tenure users face the disadvantage that even where *de minimis* use is described in terms of a right to abstract water and use it for specific purposes it will be very difficult to assert an un-quantified right against the state or other users, i.e. individual *de minimis* rights lack security and often also equitable mechanisms for allocation even where *de minimis* uses as a category are legally protected (FAO, forthcoming; van Koppen, 2007). It has been stated that they are rights only for as long as there is water available (FAO, forthcoming). Beyond recognizing *de minimis* rights as legal the protection of the significant social and public health benefits derived from small-scale uses requires effective aquifer protection measures to prevent *de minimis* sources from running dry or becoming unfit for use. As information about *de minimis* abstraction is scarce requiring well drilling to take place only on the basis of a permit provides at least information about the location of wells. A reporting regime whereby users are required to periodically provide details of their abstraction and use of groundwater also helps to keep the scope of *de minimis* uses under review (FAO, forthcoming). Community management approaches may provide further options for groundwater allocation and protection for *de minimis* uses (see 0).

4.4 Customary rights

In many parts of the world customary or local water rules function very well and are perceived as the legitimate rules in place that effectively guide the way individuals use groundwater.

Although customary rules tend to be robust and dynamic they may on their own not be sufficient to achieve higher standards of welfare or to cope with growing pressures on water resources induced by technical innovation, socio-economic drivers or environmental changes (van Koppen *et al*., 2007). Large investments or planning purposes require the increased legal security offered by formal rights. And, the livelihoods of existing users may have to be protected against new uses and users by formalizing their rights.[37] Customary law may also not be fair or non-discriminatory, particularly as far as women and non-dominant religious or ethnic groups are concerned. It entrenches gender, age, ethnicity and class differences and frequently reflects unequal power relationships in local communities.

In many instances water reform processes have therefore attempted to replace customary rules with permit-based systems, often creating conflict between the two. Reforms that ignore or even erode community-based water law risk disenfranchising rights holders and dispossessing them of their customary water rights (van Koppen, 2007). The introduction of permits that stipulate individual use rights to a resource that may be perceived as a common property resource that is to be shared may pose particular challenges. In most African customary water laws, water is considered as a community property and private ownership of such water is not recognized even though some shallow wells may be considered private (Meinzen-Dick and Nkonya, 2007). In contrast, private water rights are widely observed for groundwater in Asia. Problematic are also transition provisions such as time limits within which existing customary rights may be registered as formal rights. They do not achieve their purpose if the holders of customary rights are not properly informed of the new legal requirements or if the time provided is too short as in the case of Ghana where twelve months were granted. This period was so short that many users in rural areas did not even become aware of the new legislation and

[37] Increasingly customary rights are also threatened by foreign agri-business investments based on concession agreements backed by foreign investment treaties (FAO, forthcoming).

therefore officially lost their customary rights (Sarpong, 2004). Among the harshest criticisms is that water rights permits destroy social capital, create a tragedy of the commons and favour the administration-proficient at the expense of all others, most of all poor women (van Koppen *et al.,* 2007). Viewed together with the weakness of the administration in many countries and the high costs involved in implementing a permit system for high numbers of groundwater users, this criticism raises important concerns.

It is a key question how customary water uses can be incorporated within a formal water management framework in a way that respects and protects existing rights, avoids disenfranchising customary rights holders and takes into account existing perceptions, values and structures but also enables groundwater management decisions beyond the local level and requires permits for certain types of uses. Many open questions remain how the interface of community-based water law and public intervention could be designed so that more appropriate and effective legislative measures can build upon communities' strengths, while overcoming their weaknesses.[38]

4.5 The land-water interface

Whereas water resources are typically under state ownership or control, the right of private land ownership is a key feature in many jurisdictions. While historically water rights were essentially a subsidiary component of land tenure rights, with the introduction of administrative water rights regimes few formal links remain between land tenure and water rights regimes, except in a few jurisdictions and where customary rights prevail (Hodgson 2004). In much of Africa and Asia customary water rights are intrinsically linked to land and embedded in land tenure (Meinzen-Dick and Nkonya, 2007).

Groundwater quantity and quality protection are affected by land management. Natural groundwater recharge processes have to be protected from land-based interference and land management offers scope to regulate recharge to improve groundwater quality and quantity. Also the problem of land-based diffuse pollution underscores the importance of looking at the land-water interface when regulating groundwater. It is increasingly important to both develop and coordinate land use plans, in both urban and rural areas, with river basin or aquifer development plans.

A number of legal measures have been used to ensure that land uses do not adversely affect groundwater. Among them are: prohibition or limitation of certain polluting activities; limitations of the use of fertilizers and pesticides as diffuse sources of pollution; prohibition or limitation of certain water-using activities; restrictions of certain cropping patterns; reduction of animal-grazing intensity; land reclamation and drainage (Nanni *et al.,* 2006).

Special zoning mechanisms have become a major feature of recent legal regimes. Land surface zoning is often applied to recharge areas. It is also used for other critical areas of high vulnerability where prohibitions or restrictions to groundwater abstraction or to activities with adverse impact on groundwater, such as industrial chemical handling or effluent discharge to the ground, mining, or certain agricultural land use practices, are introduced. The protection of drinking water sources is a particularly important case in point: the capture zones of the main areas of potable water-supply abstraction require to be designated as protected areas. Zones may also be established in discharge areas, for instance to protect wetlands.

Successful zoning depends on sufficient knowledge about the characteristics of the aquifer, on land-use planning processes that take groundwater issues appropriately into account and on a set of accompanying measures that support the restrictions brought about by zoning. E.g., if a "critical area" is defined where water well drilling would be banned to prevent land subsidence, possibly combined with powers to seal water wells in areas with mains water-supply coverage, this should be combined with economic measures such as charging for groundwater abstraction according to metered (or estimated) abstraction for the remaining wells. Such measures have, for instance, successfully been taken in the Greater Bangkok Area to control urban private abstraction since the mid-1980s. They have resulted in reversing a trend of groundwater resource decline and environmental degradation (Buapeng and Foster, 2008).

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[38] See for a discussion of these issues and further references van Koppen, Giordano and Butterworth (eds.), 2007.

4.6 Stakeholder participation and (ground-)water user groups

Stakeholder participation involving a wide range of stakeholders in processes leading to new legislation or planning or in day-to-day aquifer management, can contribute significantly to effective governance outcomes. It can take the form of user self-organization with a view to managing groundwater resources at the local level. Participation has shown to yield a number of benefits ranging from more informed decisions to outcomes that are better complied with, to mobilizing self-regulatory capacity, where appropriate (Hodgson, 2006; Garduño, van Steenbergen and Foster, 2010). It raises public awareness, familiarizes with the reform, planning effort or administrative task, increases the information available to governments and, ideally, helps to generate general social consensus that fosters respect for the law and facilitates implementation through user cooperation, even in case of unpopular decisions which result in some stakeholders losing benefits (Hodgson, 2006, also providing examples from South Africa and Kyrgyzstan). It is particularly important in situations where the sheer number of groundwater users makes monitoring and enforcing groundwater rights cumbersome.

Legislation has to set out where participation will take place, how representatives are chosen and what roles they play and make sure that all stakeholders are properly represented, which may be a challenge with respect to disadvantaged groups and non-articulate small-scale users. NGOs have a potentially important role to play here and may help to keep participatory approaches alive beyond the time of externally funded pilot projects, which may be an issue (FAO, forthcoming).

In many instances the scale of groundwater issues may be quite small and local solutions be the most appropriate given the localized nature of groundwater access and use. In such circumstances local level groundwater management by self-organized user groups may be a promising and appropriate approach. For instance, the Expert Group on Ground Water Management and Ownership of the Indian National Planning Commission suggested a shift in focus from state control to community management by user groups because of difficulties of implementing a permit-based system. It recommended that user groups be responsible for planning the use of groundwater within groundwater management units and based on the goal of sustainable-yield management meaning that withdrawal should not exceed long-term recharge. The Central Ground Water Board and the State Ground Water Board would be responsible for scientific monitoring of groundwater levels and for estimating a sustainable level of groundwater use. In case water levels fell below the replenishable level the Central government could declare an area as “environmentally threatened” and in consultation with stakeholders and strategy for addressing this problem would be developed (Expert Group on Ground Water Management and Ownership of the National Planning Commission of the Government of India, 2007).

Stakeholder self-organization can occur based on strong community values and norms, particularly if embedded in and facilitated by a conducive larger regime (Ostrom, 2002). A well-informed community of groundwater users may agree on maximum acceptable drawdowns in pumped wells or ban the application of pesticides across an aquifer that furnishes potable water supplies (GEF, 2012). Local self-management will need technical support when problems occur, and preferably before, for realistic appreciations of the state of the resource. Management of groundwater resources by user groups also does not replace state regulation, implementation and enforcement, and economic mechanisms, rather the three work as a tripod on which to base aquifer governance (Meinzen-Dick, 2007). It should also be noted that there are relatively few examples of self-organization in relation to the scale and intensity of groundwater development (Moench, Burke and Kulkarni, forthcoming).

It is important that the legal framework provides options for how users can organize and clearly defines the role and responsibilities of groundwater user groups on the one hand and the water administration and other public institutions on the other. For large-scale groundwater users such as Coca Cola in the case of India a permit and registration approach with clear indications of conditions to be met should exist in parallel to community approaches (Nanni, no date). Among the organizational forms according to which stakeholder groups can be established are water users associations, groundwater user groups, village water supply groups, aquifer management organizations (AMORs) or NGOs. AMORs have been suggested for larger high-yielding aquifers and should include all local water user associations, groundwater user groups, village water-supply councils etc., and also representatives of national and/or local groundwater resource agencies and of the corresponding local government (Garduño, van Steenbergen and Foster, 2010). The governance arrangements that may work across a small aquifer may not work in large aquifers supplying water to a range of different activities in larger urban, agricultural, industrial and mining areas (GEF, 2012).

Box 8 Groundwater User Associations in Spain, the US and Mexico (COTAS)
The legislation of a number of countries provides for the establishment of (ground-)water user associations or aquifer management organizations, for instance in Spain (Lopez-Gunn and Cortina, 2006), Mexico, Australia and the western states of the US. They have been established especially where aquifers are at risk of being degraded or depleted. For instance, the Spanish Water Law of 1985 makes the establishment of groundwater user organizations compulsory in overexploited aquifers (Hodgson, 2006). In a number of western states of the US groundwater management or conservation districts, a form of water users association, have been established in respect of about 89 percent of groundwater resources. They are controlled by local users and may set limits on pumping and wells, adopt groundwater management and development policies and programmes, and propose water allocations criteria. In Mexico, where groundwater resources are severely overexploited, COTAS (Comités técnicos de aguas subterráneas – technical groundwater committees) have been created. They are civil society organizations, whose set up has been carefully facilitated by the National Water Commission and who are supported financially by the public hand. Inter alia, the COTAS support the implementation of groundwater management plans, support the government in groundwater rights administration, provide services to groundwater user, support consensus-building for future integrated water resources management and establish dialogue with and improving data on groundwater users (e.g. by helping the water administration to validate, update and correct databases on wells) (Foster, Garduño and Kemper, 2004).

4.7 Implementation and enforcement

Implementation is the key for any working water law regime and the biggest stumbling block. Without consistent implementation access to water becomes insecure. Falling water tables put livelihoods at risk and the absence of effective quality protection may render groundwater dangerous for human consumption. Water rights lose their value and cannot be used for planning purposes.

Implementing groundwater legislation is particularly challenging because of the sheer number of users involved, the difficulties of monitoring and the high financial implications. Particularly agricultural abstraction has proved impossible to regulate in countries such as China, India and Mexico. Due to insufficient implementation, particularly in developing countries, many recent water laws fail wholly or partly to work in practice thus making no or an insufficient contribution to aquifer governance. This applies even to progressive and sophisticated water laws like the 1998 South African Water Act.

A number of factors have emerged as key constraints to implementation. Among them are legal requirements that exceed the available technical, human and financial resources; formal legislation that is not well aligned with customary or local rules and thus rejected (see 0); legal frameworks that do not clearly delineate responsibilities and assign well defined tasks; and insufficient information on groundwater resources that impede informed decisions about allocation and protection measures (see 0 and 0).

Implementation requires human, administrative and financial resources. The extent to which such resources are available should be assessed before legislative steps are taken. The outcome should help to determine feasible approaches, i.e. legislative burdens that are commensurate with existing capacity. For reasons of equity and justice implementation should be uniform across a country, unless implementation in priority areas is legally allowed for specific reasons. There are examples that improving implementation of groundwater management measures in objectively-defined priority areas and not across a whole jurisdiction (which would have high administrative overhead) can be a useful approach.[39]

An effective organizational framework depends on a clear delineation of responsibilities among the institutions involved in one way or another in groundwater management and coordination among the ministries,

[39] See the example provided in Buapeng and Foster, 2008.

departments or other authorities responsible for specific or sectorial aspects of water resources. Gaps and overlaps in competence as well as lack of coordination horizontally among different ministries or vertically cross different levels e.g. from the federal to the state level, render the implementation of legislation cumbersome or ineffective. In many countries there is still a fragmented structure of governmental institutions entrusted with various water management roles, often with one ministry or authority being in charge of surface water and another (often less well staffed and financed) of groundwater. Unless roles and responsibilities are clearly defined groundwater management, let alone integrated water resources management, suffers.

Setting up accountable and transparent institutional arrangements, staffing them with skilled personnel and financing them appropriately takes time. It is important to stage the steps of introducing new rights and obligations appropriately in order to avoid signals of non-implementation and to ensure that non-compliance incurs sanctions, ranging from offences punishable by modest fines to severe offences of a criminal law nature depending on the offence, its severity and persistence and the damage caused. With patchy enforcement those who do not respect the law are often not sanctioned, thus deterring the rest of the user community from complying as well.

4.8 Water law and macro-level policies

If water law is to make an effective contribution to good groundwater governance water law and policy and social, economic, agricultural and environmental policies need to be aligned. Where economic triggers to overexploit groundwater and technological innovation meet weak water law enforcement, the result is aquifer degradation. The already mentioned example of Guanajuato demonstrates that where energy, agricultural and other policy fields provide incentives in favour of overexploitation of groundwater resources a weakly enforced water law has little influence on this process (Foster, Garduño and Kemper, 2004).

Typical examples of policies on a collision course with legal limitations include subsidies on energy tariffs (the prime example being groundwater energy tariffs in peninsular India, Garduño et al., 2011) or flat-rates encouraging increased water well pumping or incentives to intensify agriculture, including fertilizer and pesticide subsidies and guaranteed prices for certain crops, which have resulted in groundwater contamination. In situations where economic reasons nudge users not to comply with legal obligations and the water authority has no operational capacity to enforce the law, the law cannot cope by itself with the effects of counter-running economic stimuli. Rather than relying solely on enforcement in such situations it is more promising to provide incentives for users to comply with the law by aligning policy areas. Direct and indirect resource and energy pricing policies and other demand management measures can support the legal regulation of demand for groundwater and its protection through a water rights system, in particular in situations where the implementation of water permits appears unrealistic because of multitudes of users.

5. Constraints and opportunities at the international level

Remarkably few agreements have been concluded for specific transboundary aquifers and on shared groundwater resources in general. A range of factors may explain this dearth of legal instruments among them ignorance in some cases that an aquifer is transboundary, apprehension to undertake commitments with respect to resources whose characteristics may not be well known and strong perceptions of sovereignty over transboundary groundwater quite different to the generally well recognized shared nature of transboundary rivers and lakes.

5.1 Sovereignty

The paucity of international instruments addressing transboundary aquifers reflects longstanding disregard and partly ignorance of the shared nature of these resources which has changed only recently.[40] Sometimes only groundwater in the boundary area is recognized as belonging to a shared resource. In the absence of clearly defined rules and obligations international law has so far only marginally shaped the way in which states manage their transboundary groundwater systems. The vacuum has fostered an ill-founded view of almost unrestricted sovereignty over shared groundwater resources, which still looms very strongly.

This view has also influenced the ILC Draft Articles on Transboundary Aquifers. Criticized sharply by many, the principle of sovereignty is placed prominently as the first principle in the Draft Articles section on principles (McCaffrey, 2009; McIntyre, 2011). According to Article 3 each aquifer state has sovereignty over the portion of a transboundary aquifer located within its territory. Although Article 3 continues stating that the sovereignty shall be exercised in accordance with international law and the draft articles, the emphasis on sovereignty is atypical for a legal instrument on transboundary freshwater resources. It reflects an approach that seemed overcome since the infamous Harmon Doctrine[41] and replaced by the notion that states share a “community of interest” in a shared water resource to which they have a right to equitable and reasonable use.[42] Most likely the indiscriminate focus on aquifers without distinguishing rock and water together with the invisible and ubiquitous nature of groundwater whose transboundary and often very slow flow remains hidden to the eye has been conducive to the unfortunate resurrection of claims of sovereignty. It is noteworthy that the first aquifer agreement following the draft articles, the Guaraní Aquifer Agreement, places strong emphasis on the notion of sovereignty in reflection of some deeply rooted convictions prevailing in the region.[43] At the same time, it recognises that a transboundary aquifer requires cooperation among the states sharing it and serves as an example how such cooperation may be styled.

5.2 Formats of cooperation

It is at the level of specific transboundary aquifers that cooperation can generate the most tangible and short-term positive impacts on groundwater governance. The ILC draft articles provide a general framework that needs to be fleshed out considerably in the application to specific local conditions and challenges.

Where a treaty seems one step too far or too cumbersome an incremental approach or more informal arrangements not (yet) backed by formal legal instruments or priority action along the border region can be useful options.[44] An evolutionary process for arriving at an aquifer cooperation mechanism was taken in the cases of the SASS and the Iullemeden aquifer system. Cooperation can also grow at the more local or even municipal

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[40] A UNECE map of a survey of European transboundary aquifers shows that a number of aquifers had only been indicated by one country as being transboundary. UNESCO (2001), p. 12.

[41] For a detailed discussion of this issue see S. McCaffrey, “The International Law Commission Adopts Draft Articles on Transboundary Aquifers”, 103 *American Journal of International Law* (2009) p. 272, 289.

[42] The principle of community of interest was introduced by the Permanent Court of International Justice in the River Oder case and reaffirmed by the International Court of Justice in the Gabčikovo-Nagymaros Project case. *Territorial Jurisdiction of the International Commission of the River Oder*, 1929 PCIJ, Series A, No. 23, p 27; *Gabčikovo-Nagymaros Project (Hungary/Slowakia)*, Judgement, I.C.J. Reports 1997, p. 7, 56.

[43] See Article 2 and Articles 1 and 3.

[44] Border Groundwater Agreement between South Australia and Victoria (15 October 1985), http://faolex.fao.org/.

level. Arrangements have been crafted on the Hueco Bolson between the City of El Paso and Ciudad Juárez on the border between Mexico and the USA,[45] and on the Abbotsford-Sumas Aquifer between the US State of Washington and Canadian Provence of British Columbia.[46] For the Hueco Bolson aquifer the memorandum of Understanding has been concluded between the municipal water utilities on each side of the border (for a discussion see Eckstein, 2011). For the Abbotsford-Sumas aquifer the memorandum of understanding was signed at state/provincial level and it is made explicit in the text that it is a non-binding agreement. Also within the framework of the Guaraní Aquifer project local transboundary cooperation was established in four pilot areas (Proyecto Sístema Acuífero Guaraní, 2009). Such arrangements can serve to initiate communication, cooperation, implementation of projects of joint interest, and data and information sharing.

Instead of embarking on a self-standing agreement in many circumstances it may be more feasible to increase cooperation on groundwater issues under the umbrella of an existing treaty, possibly supplemented by a protocol on groundwater or technical guidelines, and to incorporate groundwater in the mandate and work of already established basin institutions.

5.3 Benefit sharing and other lessons learned

Lack of real or perceived cross-border issues to be tackled or lack of perceived benefits to be gained from cooperation provide disincentives to transboundary cooperation. Only if cooperation is likely to yield more tangible benefits than individual country action is there an incentive to cooperate, to make (legally binding) commitments and to honour them. The Genevese Aquifer Agreement is a good example of a benefit-generating undertaking: both sides benefit from the capacity of the aquifer to purify artificially recharged water.

There are also other lessons to be learned from the rich corpus of surface water treaties (Paisley, 2002; Fox and Le Marquand 1978). A review of the experience of a large number of GEF transboundary freshwater and marine legal and institutional frameworks has distilled the following key factors for working treaty arrangements in addition to benefit sharing: information and data exchange, the existence of a dispute resolution mechanism, sustainable financing, good institutional design at the technical and political level, the adaptability or flexibility of the treaty and public participation (Paisley *et al*., 2011).

5.4 External support

It is noteworthy that with the exception of the Genevese Aquifer treaties, all agreements for specific aquifers concluded until present were preceded by large externally funded projects which had a substantial component of knowledge generation and study of the shared resource and which aimed at data and information collection and exchange.[47] As only what can be measured can be managed, the emphasis on knowledge generation and data sharing seems sound. The importance of monitoring is underscored by the 2000 UNECE Guidelines on Monitoring and Assessment of Transboundary Groundwaters (UNECE, Task Force on Monitoring and Assessment, 2000). An initial phase with emphasis on technical issues is a good prerequisite to establishing a basis for further cooperation and to building trust before moving towards a more formal agreement. Where needs are pressing, the call for more data and information should, however, not turn into an alibi for inaction.

For developing countries cooperation over transboundary aquifers will often require external financing and support by international agencies as the experiences of the Nubian Sandstone Aquifer System, the SASS, the

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[45] Memorandum of Understanding between City of Juárez, Mexico Utilities and the El Paso Water Utilities Public Services Board of the City of El Paso, Texas, 6 December 1999, available at: http://internationalwaterlaw.org/documents/regionaldocs/Local-GW-Agreements/El_Paso-Juarez_MoU.pdf.

[46] Memorandum of Agreement related to referral of water right applications related to the transboundary Abbotsford–Sumas Aquifer between the State of Washington as represented by the Department of Ecology and the Province of British Columbia as represented by the Minister of Environment, Lands and Parks, 10 October 1996, available at: http://internationalwaterlaw.org/documents/regionaldocs/Local-GW-Agreements/1996-BC-WA-Water-Right-Referral-Agreement.pdf.

[47] The characteristics of the Genevese aquifer were already well known when the parties entered into the 1977 Arrangement.

Iullemeden Aquifer System and the Guaraní Aquifer System show. As these developments are still fairly recent an assessment of the degree to which project-support agreements will be implemented and retain long-term viability remains to be undertaken in the future.

5.5 Guidance from global and regional legal frameworks

Where no treaty exists for an aquifer, regional and global legal frameworks come into play. For the time being the Draft Articles on the Law of Transboundary Aquifers are the most important document containing rules of a general nature for shared groundwaters. Potentially, the draft articles may become the starting point for the development of a globally binding convention. Whether such is feasible and desirable in the coming years is still open. On the one hand, given the immature state of international groundwater law generally, rushing towards a convention might be premature. One the other hand, a well crafted convention supported by a number of important aquifer states would provide impetus to the development of further agreements for specific aquifers. The same can to some degree already be said of the Draft Articles as the reference to the Draft Articles in the Guaraní Aquifer Agreement demonstrates. For the time being the draft articles are the most authoritative codification of international groundwater law and recommended by the General Assembly. They make it very clear that transboundary aquifers are shared resources that have to be managed as such.

Developments at the global level should be supported by progress at the regional level, where especially the ongoing initiative of the UNECE to develop model provisions on transboundary groundwaters to supplement the 1992 UNECE Water Convention might result in concrete outcomes. The members of the European Union already have committed to a very stringent approach to groundwater protection.

Compared with the regime available for the protection of other natural resources where conventions with clear and detailed rights and obligations, regular meeting of parties and well-working secretariats are in place and have shaped domestic laws and policies, the potential of international law to contribute to the governance of transboundary aquifers remains still to be developed.

Part 3 Prospects

This last part will look towards the future and suggest some issues whose relevance is likely to increase.

6. The domestic level

A need for appropriate legal frameworks to govern groundwater is sharply felt. More and more, the assumption that permit systems are the best way forward in all circumstances to address issues of groundwater scarcity and degradation is challenged. More creative approaches have to devised be to get a handle on the *de facto* open access nature of groundwater in many countries. Nuanced and sophisticated discussions about the respective roles of permit systems, customary rules and community approaches are likely to gain in importance if the challenge of groundwater abstraction by multitudes of small-scale users in many developing countries is to be addressed.
To the extent that groundwater resources are becoming overly used and polluted environmental concerns are likely to take a more and more prominent role in groundwater legislation, something that could already be observed with respect to water law in general over recent decades. In particular developments in the European Union bear out such a tendency.

The effects of climate change might require new regulatory answers to the challenges arising from it, domestically and with respect to transboundary resources. It will have to be explored what role the law will be able to play in enhancing adaption strategies and mitigation actions.

Since the adoption of General Comment No. 15 by the United Nations Committee on Economic, Social and Cultural Rights the debate about the human right to water has been growing. It has received further support when the United Nations General Assembly affirmed the right to water in Resolution 64/292 in 2010. The discussion about the rights to water might have more and more repercussions for water policy and legislation as experience gained from the right to food shows. Water will increasingly be looked at from a human rights perspective and policies and laws be measured against human rights criteria, particularly with respect to non-discrimination.

Use of the subsurface is growing aided by new technologies and often with implications for aquifers. Examples are tapping deep seated aquifers that until present have been used only sparsely for abstracting freshwater but also extracting minerals, oil and gas; developing geothermal energy; hazardous waste disposal; storage and recovery of substances and heat; and accommodating technical infrastructure. These activities are likely to result in new requirements for legal regulation, domestic and international as far as transboundary aquifers are implicated (van der Gun, Merla, Jones and Burke, 2012).

7. The international level

With growing pressure on groundwater resources, the extent of cooperation with respect to specific transboundary aquifers is likely to increase as is the number of treaties or other legal arrangements. It is at the level of bi- and multilateral international legal cooperation that tangible outcomes can best be achieved. Cross-country cooperation may take a number of forms from informal cooperative approaches to joint activities following the adoption of a fully-fledged treaty. Timely cooperation will offer opportunities to mitigate harm early and to avoid crisis situations. Developing countries are likely to require donor assistance when embarking upon such an endeavour.

The adoption of the draft articles on transboundary aquifers and their endorsement by the United Nations General Assembly has created a momentum of attention to transboundary aquifers that might lead to further initiatives trying to craft legal tools to meet the challenges of groundwater governance. The UNECE initiative to develop model provisions on transboundary aquifers can be seen in this context. As there are only few legal examples to seek guidance from, progress in this field is, however, likely to remain incremental.

At the global level, the Draft Articles on the Law of Transboundary Aquifers might in time lead to the adoption of a framework convention on transboundary aquifers as has been the case with legal instruments developed by the International Law Commission in other fields. The fate of the Draft Articles will be influenced by progress made at regional and aquifer level. If a convention is negotiated its effectiveness will depend on a range of factors. Arguably, it could be greatly enhanced by a regular meeting of parties and the existence of a secretariat which have become common features of environmental treaties.

8. Conclusions

Legal frameworks that are well tailored to the specific local context are indispensable for groundwater governance. Worldwide there is a tendency to modernize water laws and to pay more attention to groundwater management and protection in domestic legislation.

With the exception of a few jurisdictions groundwater resources now tend to be vested in the state or put under state control although this may not be felt at all at the local level. Government administered legislation tends to replace property minded doctrines and permit-based access to groundwater resources has become a standard approach. Such administrative water rights systems work very well in high-income countries with highly formalized water economies where also registration, metering, charging and other obligations are easy to implement. Yet, highly complex requirements such as those of the EU Water Framework Directive and its daughter directive on groundwater remain challenging even for EU member states.

Approaches that work in circumstances such as in the United States and in Australia which are characterized by small numbers of large users and low population density have often failed in other regions such as Asia with high population density, *de facto* open access to groundwater, little information about the characteristics of aquifers and multitudes of tiny private users. In much of Asia and Africa local and customary rules shape individuals' approaches to groundwater. It is a key question how to incorporate *de minimis* abstractions, customary water uses and local level institutional arrangements within a formal water management framework. Such incorporation should respect and protect existing rights, avoid disenfranchising customary rights holders and take into account existing perceptions, values and structures. At the same time it should enable groundwater protection and management decisions beyond the local level and the use of permits for certain types of uses. In addition, less complex provisions, staged implementation, implementation in priority areas and community-based management by user groups may be explored. All water governance mechanisms should be accountable, transparent, participatory and non-discriminatory and function in an integrated manner taking into account the implications of the land-water interface.

Trite as it may sound, it also has to be remembered that what has worked in one place, often fails in another place where resource systems, governance systems, resource units, and users are different (Meinzen-Dick, 2007). General key factors for laws that work in practice are high quality of the legal provisions, which address all relevant issues and are fair, equitable, coherent and enforceable; well-sequenced and planned processes of transition and change; operational capacity of the water administration to implement the law; social consensus that supports compliance; stakeholder participation in legislative, planning and management processes, including user groups; and coherent and supportive wider socio-economic trends and policies. Ample experience from around the world has made it abundantly clear that water law only works if it is flanked by supporting policies, awareness raising, technical solutions and, very importantly, the human, administrative and financial structures for its implementation. For many countries and situations this is a tall order with important socio-economic and financial implications. These costs need, however, to be offset against the costs of inaction that will often still be higher – and most likely be borne by those who are already disadvantaged.

For the governance of transboundary aquifers the development of International law has only lately picked up pace. While until a few years ago it offered very little guidance on how to manage and protect transboundary aquifers, recently developments at the global, regional and transboundary aquifer level have marked the beginning of a phase in which international law might begin to play a bigger role in governing these resources. Nonetheless a shift at the transboundary level from notions of sovereignty to the notion of a shared resource is yet to take hold in many regions. Important inroads are being made with regard to specific transboundary aquifers and also at the regional and global level. These developments seem to herald acceptance of the shared nature of problems, whether they be of overdraft or of pollution or both, or the mere anticipated threat of them, across the borders. States have geared up to deal with them in cooperative or coordinated fashion in a number of ways from informal arrangements to a few bi- and multilateral treaties for specific aquifers. With respect to tangible governance outcomes and immediate benefits to be realized cooperation at the aquifer level is most desirable, ideally guided by regional and global instruments, including most notably the landmark draft 2008 Articles on the Law of Transboundary Aquifers developed by the International Law Commission.

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Trends in Local Groundwater Management Institutions

Digest

Relevance

The formation of local institutions around groundwater sources has a long legacy, rooted in common groundwater development around shared springs, hand-dug wells, *adits* and *falaj* systems. Today, many of the local institutions and related customary habits are still active and relevant where groundwater use is relatively 'light' and still conditioned by traditional or non-energized groundwater abstraction. But as indicated in Thematic Paper 8, the advent of the mechanized pump has changed many of these presumptions. Whether natural resource policy and administration, water law and specific groundwater legislation (the institutional environment) has caught up is one question, as discussed in Thematic Papers 5 and 6, but a more important question to ask is whether customary practices amongst groundwater users (i.e. the specific institutional arrangements) have also caught up.

Discernible trends can be observed in the evolution of local groundwater management institutions and their effectiveness in sustaining the practice of groundwater use. Private use has been strong driver for groundwater demand and while there have been successes in managing groundwater at local levels, these are scattered and appear to depend heavily on location specific institutional, technical and economic conditions. In addition, many groundwater management responses are difficult to take to scale given the 'granularity' of aquifer settings.

The array of local adaptation and their governance arrangements

Early (pre-historical) organization around accessible groundwater can be inferred from archaeological evidence but the first recorded signs of governance arrangements specifically moulded around groundwater comes from the arid and semi-arid zones where customary laws set patterns and priorities for groundwater access and use. Social collaboration around manual, low-lift technologies for potable supply continues but the impact of widespread energised pumping in the mid 20th Century saw progressive 'privatization' of groundwater supplies – in rural and urban areas. There are few examples of wholesale governance responses that can claim to have been successful in addressing the combined local problems of depletion and pollution.

The declaration of public and private interests in groundwater has been pivotal in determining not only the pace and intensity of groundwater development (see Thematic Paper 6); it has also conditioned a set of private and community responses. The basic 'rule of capture' for private landowners has dominated and entrenched habits of individual use and expectation. Only in Muslim traditions has the 'right to thirst' systematically protected the third party use of groundwater. While this dominance of private interests has persisted into the 21st century, the declarations of public interest in groundwater and aquifer protection find their origin in the protection of public water supply and related public health legislation. Agricultural use has generally remained immune from governance in the public interest for much of the 20th century.

Observed trends in water and groundwater legislation confirm an overall preference to put groundwater squarely in the public domain – to the extent that public registration of groundwater use is required. However even when a *prima facie* case for conserving strategic aquifers exists and regulatory provision is made, actual management can be confounded by persistent 'non-compliance'.

Governance constraints and opportunities

In many developing countries, public agencies responsible for mitigating or otherwise addressing the impact of water scarcity have limited capacities. As a result, populations depend primarily on the resources available within communities and wider social networks. A variety of extended family and patron–client relationships exist that help individuals and families cope with the impact of water scarcity. These networks entitle members to key resources for coping but are essentially informal.

There have been few formal planning approaches that anticipate loss of vital groundwater services – many responses have come when it is too late to claw back the desired level of groundwater service. Where more formal attempts have been made to address crises of depletion and/or pollution, there are often strong incentives to not undertake collective management of common groundwater resource. Indeed, where groundwater use is intensive and critical for economic productivity are precisely the areas where it can prove impossible to relax an aquifer.

Both informal and formal approaches are still valid and can be adapted to local aquifer conditions and societal preferences. In this sense the range of governance option has been broadened and the palette of governance mechanisms much richer.

Prospects

Conventional water-focused approaches to groundwater management represent only a portion of the policy and institutional space that is available for responding to emerging problems. Many of the impacts associated with emerging groundwater problems depend on a much wider array of social and economic conditions. Consequently, adaptive interventions that affect those wider conditions may be as important for mitigating the impact of groundwater depletion or degradation as those directly affecting the groundwater resource base itself. Approaches which are directed at controlling the resource base and its use may, in fact, have limited application in effecting groundwater resource management.

At the other end of the spectrum lies the relatively unexplored policy space of adaptation. It is this space that requires greater attention, given the rates at which groundwater is being developed and the anticipated impacts of climate change.

Conceptually, three broad, complementary and often overlapping sets of 'adaptive' strategies are possible for responding to the limitations associated with the more conventional or direct management strategies discussed. These are:

- *Incremental approaches to groundwater management.* Strategies are adjusted continuously as new information emerges or conditions change.
- *Indirect management strategies.* Strategies that emphasize opportunities for influencing groundwater use by shaping the context in which groundwater use occurs. They include strategies, such as power pricing, that are part of many conventional management strategies. However, they also include power rationing and potential opportunities for shaping groundwater use through high-level policy and economic changes (such as crop price supports).
- *Specific adjustment to groundwater conditions.* Strategies that emphasize opportunities for adapting social and economic systems to groundwater conditions and dynamics rather than the other way around. These strategies take groundwater conditions as largely given and seek to identify opportunities for reducing or mitigating problems through changing the social and economic context of use.

Conclusions and messages

Trends in local groundwater management institutions cannot be assessed systematically due to the scattered nature of available information. Instead, stocktaking has to rely on anecdotal evidence pulled together from disparate sources and geographies. This disparity exists at different scales – regarding aquifer systems within a contiguous region or across countries. Overall, however, it is clear that local or aquifer-based groundwater user management has been an area of policy neglect. A general conclusion from the baseline literature and this diagnostic is that autonomous self-regulation is unlikely to have any impact, unless the institutional environment is conducive and the rights and obligations with respect to groundwater and groundwater protection are accepted. Furthermore, available experience suggests that even if local policy and resource management issues are addressed, local arrangements will, for a variety of social, economic, institutional and political reasons, be insufficient to address the governance 'gap' required to conserve resources and prolong groundwater-dependant livelihoods. To put it more bluntly, conventional approaches to groundwater management appear insufficient to address emerging depletion, pollution and other groundwater problems.

The analysis in this Thematic Paper suggests that the inadequacy of conventional groundwater management approaches reflects the complex array of social, economic, institutional and political as well as technical factors that determine interests, access and the ability for any group to exercise a degree of control over groundwater conditions. There are inherent limitations to any approach that seeks to protect human interests in groundwater, or any other major natural system, through approaches to management that are 'resource-focused'. Groundwater is, furthermore, a particularly complex resource where, unlike surface water, groundwater access is determined by a combination of overlying land use/ownership patterns and 'invisible' and difficult to assess hydrogeological structures and processes. As a result, access is spatially highly distributed with few of the clear social/institutional control points that are present in surface water networks. This creates often-fundamental challenges for the development of institutional rules and organizations that would be required to manage the resource directly. This challenge is intensified because most management approaches emerge from technical considerations related to the groundwater resource base and are also poorly linked to livelihood strategies and the incentives that local populations actually face in relation to groundwater use. For these reasons, the development of a wider policy perspective is essential to frame 'good groundwater governance'.

What does "development of a wider policy perspective" mean? Primarily it means that approaches for addressing actual or emerging groundwater problems need to focus beyond the resource base itself and engage effectively with the social and economic context that shapes incentives for groundwater use amongst communities of users. Achieving effective management outcomes, we believe, depends on the wider governance environment and the development and livelihood choices that environment generates. Broad recognition of, for example, regional water scarcity can serve as a basis for decisions on regional economic development that emphasize low water intensity livelihoods. This type of approach, which focuses on to the wider overall environment governing development pathways, represents an arena of potential opportunity for addressing groundwater problems that is quite distinct from and relatively less explored than more narrowly focused technical groundwater management strategies. Furthermore, governance frameworks that enable societies to make this type of choice could reduce dependence on groundwater while also potentially creating opportunities for more direct conventional management of the resource base. Clearly, this does not mean moving away from developing improved understanding of the resource; rather, it means improved understanding leading to a much wider thinking about responses to groundwater-related problems rather than a focus on the resource base itself. Groundwater-specific management goals may need to look beyond straightjacket regulatory mechanisms and look for alternative niches in livelihoods, energy use and opportunities offered under adaptation and coping strategies that focus on events such as droughts, floods, economic drivers and even climate change and variability. For this to happen, public and private institutions will have to learn to work effectively with groundwater users and groundwater management organizations. The formation of 'institutional homes' for groundwater at all levels could merit more attention in the future.

Two messages emerge:

1. There are few unequivocal 'best practices' for groundwater management. Instead it is more effective to focus on strategies that are appropriate for different sets of physical, institutional, economic and

social conditions. To move up a level requires entry into the governance arena and this involves legislation and institutions (rules of the game), not just organizations.

2. Rather than managing the groundwater resource base *per se,* it may often be more effective and viable to address or mitigate the impacts of changes in groundwater conditions through courses of action that are social, political or economic and fall outside the arena of direct water management.

Thematic Paper 7

TRENDS IN LOCAL GROUNDWATER MANAGEMENT INSTITUTIONS

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Acronyms

BP	Before Present
COTAS	Comités Técnicos de Aguas Subterráneas
DWR	Department of Water Resources of California, USA
FAO	Food and Agriculture Organization of the United Nations
GWP	Global Water Partnership
IWRM	Integrated Water Resources Management
MRA	Maltese Resources Authority
RNFE	Rural non-farm economy
UNFPA	United Nations Population Fund
USA	United States of America
VIKSAT	Vikram Sarabhai Centre for Development Interaction

Key messages

1. Private use has been a strong driver of demand for groundwater and aquifer services despite the common property nature of the resources. While there have been successes in managing groundwater at local levels, these are scattered and appear to depend heavily on location specific institutional, technical and economic settings.

2. Even if a system of governance is in place, many groundwater management responses are difficult to take to scale given the 'granularity' of aquifer settings.

3. There are few unequivocal 'best practices' for groundwater management. Instead it is more effective to focus on strategies that fit the local aquifer context and patterns of use. To move up a level will necessarily involve entry into the governance arena invoking legislation and institutions (rules of the game), not just organizations.

4. Rather than managing the groundwater resource base *per se,* it may often be more effective and viable to address or mitigate the impacts of changes in groundwater conditions through courses of action that fall outside the arena of direct water management.

1. Introduction

The formation of local institutions around groundwater sources has a long legacy, rooted in common groundwater development around shared springs, hand-dug wells, *adits* and *falaj* systems. Today, many of the local institutions and related customary habits are still active and relevant where groundwater use is relatively 'light' and still conditioned by traditional or non-energized groundwater abstraction. But as indicated in Thematic Paper 8, the advent of the mechanized pump has changed many of these presumptions. Whether natural resource policy and administration, water law and specific groundwater legislation (the institutional environment) has caught up is one question, as discussed in Thematic Papers 5 and 6, but a more important question to ask is whether customary practices amongst groundwater users (i.e. the specific institutional arrangements) have also caught up (Shah, 2007).

This brief account of groundwater institutions attempts to point to the discernible trends in the evolution of local groundwater management institutions and their effectiveness in sustaining the practice of groundwater use. It looks at the scope for securing benefits through improved governance within institutional arrangements and examines the prospects for implementing such improvement.

For reference, the concept of groundwater governance is discussed in Box 1 below and a final version that has been adopted by the project is given.

Box 1: A working definition of groundwater governance

Groundwater governance has been defined as: the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck, 2007).

This working definition is, however, quite limited and does not capture the wider context of political and power relations or social drivers that determine outcomes – whether those outcomes are achieved through proactive "management" of the resource or emerge as a direct or indirect consequence of power dynamics and social, political and economic relations. Good governance can be understood as a context in which the mechanisms through which power is exercised and decisions taken are equitable and enable input from diverse sections of society *and* that it is effective – i.e. that decision making processes are as efficient as possible and enable the fundamental goals of society to be met. It is, as a result, both about processes and outcomes. Proactive management of groundwater may be one element of this but other, less management focused, approaches are also central components of the governance equation.

Given the above, the wider definition of groundwater governance adopted by the project is: The process through which groundwater related decisions are taken (whether on the basis of formal management decisions, action within markets, or through informal social relations) and power over groundwater is exercised. A "good" groundwater governance environment is one where governance processes equitably reflect the voices and interests of stakeholders (including regional and global stakeholders with interests in resource sustainability) and where broadly supported courses of action can be implemented in an effective and equitable manner.

The Technical Paper is organized in three parts: Part 1 (Baseline) presents a broad overview of the types of local groundwater institutions and identifies a set of key drivers for such local organization around groundwater; Part 2 (Diagnostic) provides a review of the most relevant constraints to and opportunities for improving governance at local scales and addresses a few specific issues; Part 3 (Prospects) attempts to identify where positive responses are likely to be deployed with most effect.

Part 1 Baseline

2. The Legacy of Early Organization around Groundwater

With few exceptions, groundwater abstraction around the world remained at relatively shallow depth until the end of the 19th century, or even much later in some countries. Apart from diverting water from springs, groundwater mostly used to be tapped by dug wells – rarely deeper than 50-100 m, where water was lifted by human or animal traction – or by infiltration galleries (e.g. *qanats* – tens of meters below surface). Technology for deeper abstraction was not yet available and knowledge on the presence of any aquifers beyond the near surface was in most cases non-existent.

From the start, man relied on open access to springs, river baseflow and shallow groundwater stored in sandy dry riverbeds for their main dry-season water sources. It is, therefore, reasonable to assume early man established strategies to ensure safe access to these water supplies. There is evidence of their limited means for collecting and transporting water. Until recently, the Australian Aboriginal cultures, with no ceramic technology, used animal skins, delicately folded and stitched leaves, tree bark containers, wooded bowls and sea, egg and coconut shells as containers.

Society's systematic exploitation of groundwater for domestic and cattle watering coincided with the transition from forager to sedentary farmer. This followed the domestication of livestock and food plants between 9 000 and 11 000 years BP. Water availability was central in determining man's settlement pattern. The group of 5-m-deep water wells of this age uncovered in Cyprus, and elsewhere in the Near East, reflects a certain understanding of shallow groundwater occurrences. This was likely linked to experience gained when mining of flints and later, metallic minerals for tool making. The establishment of settled farming inherently engendered the concepts of individual or communal ownership of land and water points that required protection by physical force or a system of customary law. Incidentally, it also strengthened the facets of *augmentation and protection* often through implicit systems. Such systems that looked at a larger arena of resource augmentation and protection perhaps saw the first strains of 'governance'.

Archaeological evidence shows the rapid diffusion of all forms of technological advances across North Africa, the Middle East, Arabia, Western Asia, and the Indus Valley and beyond between 10 000 to 4 000 years BP. Parallel technological developments occurred independently across Eastern Asia and South America. By 4 000 BP, wood-lined, hand-dug water wells were in routine uses for community water supplies.

Under differing regional climatic regimes, three main forms of land use evolved:

1) dry land (rain-fed) arable farming developed in the tropical and temperate humid zones;
2) surface water irrigation spread along the major river valleys around 8 000 years BP and more localised pockets of groundwater spring based irrigation developed in the more arid parts of Southern Arabia and along the Persian Gulf;
3) in the sub-humid and semi-arid zones, nomadic pastoralists relied on seasonal vegetation cover and surface and groundwater sources.

Ample surface and groundwater sources are found in rain-fed farming areas and potentially supported the high population densities as seen in the African Lakes Region. In the tropical arid and semi-arid zones from North Africa to Central Asia, a weakening of the southwest monsoon around 5 700 BP caused a regional decline in precipitation. The climate shifted from sub-humid to semi-arid and arid and the woodlands and savannah grasslands across a broad swath of the northern Sahara Desert retreated. The pastoralist and dry land farming population moved east to the Nile Valley where they merged with a fast developing surface water irrigation farming culture that mirrored the cultures in the Tigris-Euphrates Valley and the Indus Basin (Bazza, 2007).

2.1 Social cohesion in arid zones – The imperative of scarcity

The evidence of traditional social cohesion around groundwater continues and has been most marked in the rural arid and semi-arid zones where forms of water administration have had to address physical scarcity (FAO, 1978) and shown broad scale cultural responses. Accounts from Yemen where mechanized technologies and the ready availability of diesel (Taher *et al*., 2012) illustrate the importance of tradition but also the capacity to draw up new rules to meet new challenges. Experience from arid developed countries are perhaps less documented (for instance, the south-western USA, and Mediterranean) where intensity of use and rural dependency may have been less pronounced, but systems of abstraction can still be basic (hand-pumps or windlass arrangements). These modes have not transitioned to urban areas where the need to source groundwater from dedicated well-fields have had to rely on utility models and, in many cases, on the supplementary input of desalinated water. But this scale and concentration of use has also brought about the accumulation of wastewater streams and additional percolation of landscaping water. Shallow groundwater rise and pollution from untreated sewage disposal or leakage from sewers are common groundwater problems in many arid-zone cities.

2.2 The impact of low-lift technology and social collaboration

The degree to which the progressive introduction of low-lift (non-mechanized) technologies encouraged social collaboration and rule-setting for commonly-owned and -operated groundwater infrastructure is difficult to track in detail. The account given in Thematic Paper 8 indicates evidence of many collaborative initiatives related mainly to both water supply and agricultural use.

With the availability of cheap hand-pumps and shallow groundwater, even poor village communities will opt for individualized on-the-doorstep boreholes and hand-pumps. Taken with the evidence of a trend in private self-supply in urban areas which appears to be global (Foster *et al.*, 2010, Foster *et al* 2012 – FAO paper), the preference for private access to readily available groundwater seems overwhelming, when no alternative sources are available or when access to a polluted source is considered preferable to higher quality water from water vendors.

The experience of groundwater-based rural water supply in sub-Saharan Africa has been instructive as various solutions for reliable but low-cost manual-lift pumps have been attempted together with attempts to reduce drilling costs. Low-cost and low maintenance technology will continue to be important in mobilizing the low transmissivity aquifers associated with the weathered horizons in basement complex.

2.3 Transitions to mechanized pumping with access to modern technologies

It has been argued that, irrespective of the legal status of groundwater, private interests have shaped the patterns of demand for groundwater (Burke and Moench, 2000). The evolution of these intensely local interests has resulted in a set of identifiable stages. Table 1 outlines the stages of development of the rural non-farm economy (RNFE).

In this sequence, groundwater development would play a particularly critical role, enabling the transition from traditional to locally-linked, but agriculturally-led, non-farm economic development. By enabling farmers to increase production, income and income security, groundwater development would serve as the core engine for rural populations to acquire the wealth necessary for the non-farm economy to grow. Once this has occurred, much depends on the interaction between the groundwater development sequence and the non-farm economic development sequence.

For example, if the availability of groundwater declines when urban areas have a competitive advantage (during the third stage of development), high levels of push migration by farmers to urban areas might be expected. This would also occur if wells went dry, when droughts occurred in regions where water levels had been declining. In contrast, if groundwater remains available throughout all stages of development of the rural non-farm economy, then agricultural economic activities displaced by depletion or degradation of the groundwater resource base may be smoothly absorbed by new non-farm opportunities, and there may be fewer push factors creating an incentive for migration into urban livelihoods.

However, push factors are only one component in the transition now occurring in many regions. Globally, trends towards urbanization are driven by a variety of factors that include the "pull" of urban jobs, urban facilities (e.g. education and health care) and urban lifestyles. In many rural areas, groundwater development may be contributing to the urbanization process, by allowing rural residents to accumulate the capital necessary to

Table 1. Development of the rural non-farm economy

Stage of RNFE	Stage of agricultural development	Level of rural remoteness	Level of urbanization	Main locus of non farm production	Level of non-farm technology, capitalization and returns
One – Traditional	Pre-modern & subsistence	High	Low	Rural (RNFE limited by low purchasing power)	Low: traditional subsistence products
Two – Locally linked	Modernizing and expanding: initial technology-led agricultural growth	High	Low	Rural (RNFE expands through agricultural-led growth)	Low to medium: Some technology and capital improvements
Three – Leakages to urban area	Modernizing and expanding: improved urban marketing	Low (new roads open urban markets)	Low	Urban (RNFE competed away by urban goods and services)	Medium to high: as urban location allows investment and economies of scale, RNFE must modernize to survive
Four – New urban linkages	Modernizing and expanding: increasing urban demand	Low	High (congestion and costs rise)	Shift to rural: Flexible specialization able to exploit to rural advantage	Low to high: From cottage industry outworkers to modern "clustered" and subcontracted units

Source: Start (2001).

successfully migrate and obtain access to the real and perceived benefits available in urban areas. One of the first investments that rural residents often make when they obtain sufficient income is in education. As interviews in drought-affected areas suggest, this is often part of a generational strategy at the household level to ensure that at least one family member has access to non-agricultural employment (Moench and Dixit, 2004). In many regions of India, this trend is seen, even on a day-to-day basis, when many rural people travel to cities for various non-agricultural occupations including labour, services and even small enterprises such as running taxis and auto-rickshaws.

Notwithstanding the difficulty in separating the push *versus* pull factors that take people away from ancestral rural homes to towns and cities, groundwater-related problems are significant in making rural people take these decisions. Similar patterns also emerge with respect to the development of urban-based businesses and access to urban labour opportunities. As families enable more of their members to move into in urban livelihoods (whether *via* education or other routes), social networks are established that reinforce the transition. Early migrants facilitate the shift for other members of their extended kinship or caste groups. These shifts are probably financed by a combination of income from new urban-based activities and intensive groundwater-based agriculture in rural areas. Again, the core role of groundwater in this transition hinges on its lead role in decreasing the variability in agriculture, enabling agricultural intensification and allowing rural populations to accumulate the capital necessary to diversify into urban-based activities. At the same time, it becomes important to understand how this impinges on the urban water demand and the nature of groundwater use as a consequence of rapid changes in such demand. Much of such rural-to-urban shifts, in large parts of India, for instance, may simply have moved the foci of groundwater abstraction from rural areas at least to peri-urban zones; such zones have now clearly become zones of various 'informal' groundwater transactions and even complex markets.

2.4 Public *versus* private interests

The declaration of public and private interests in groundwater has been pivotal in determining not only the pace and intensity of groundwater development (see Thematic Report 6); it has also conditioned a set of private and community responses. The basic 'rule of capture' for private landowners has dominated and entrenched habits of individual use and expectation. Only in Muslim traditions has the 'right to thirst' systematically protected the third party use of groundwater (FAO, 1978). While this dominance of private interests has persisted into the 21st century, the declarations of public interest in groundwater and aquifer protection find their origin in the protection of public water supply and related public health legislation. Agricultural use has generally remained immune for much of the 20th century.

3. Institutional Models in the 20thCentury and their Socio-economic Impact

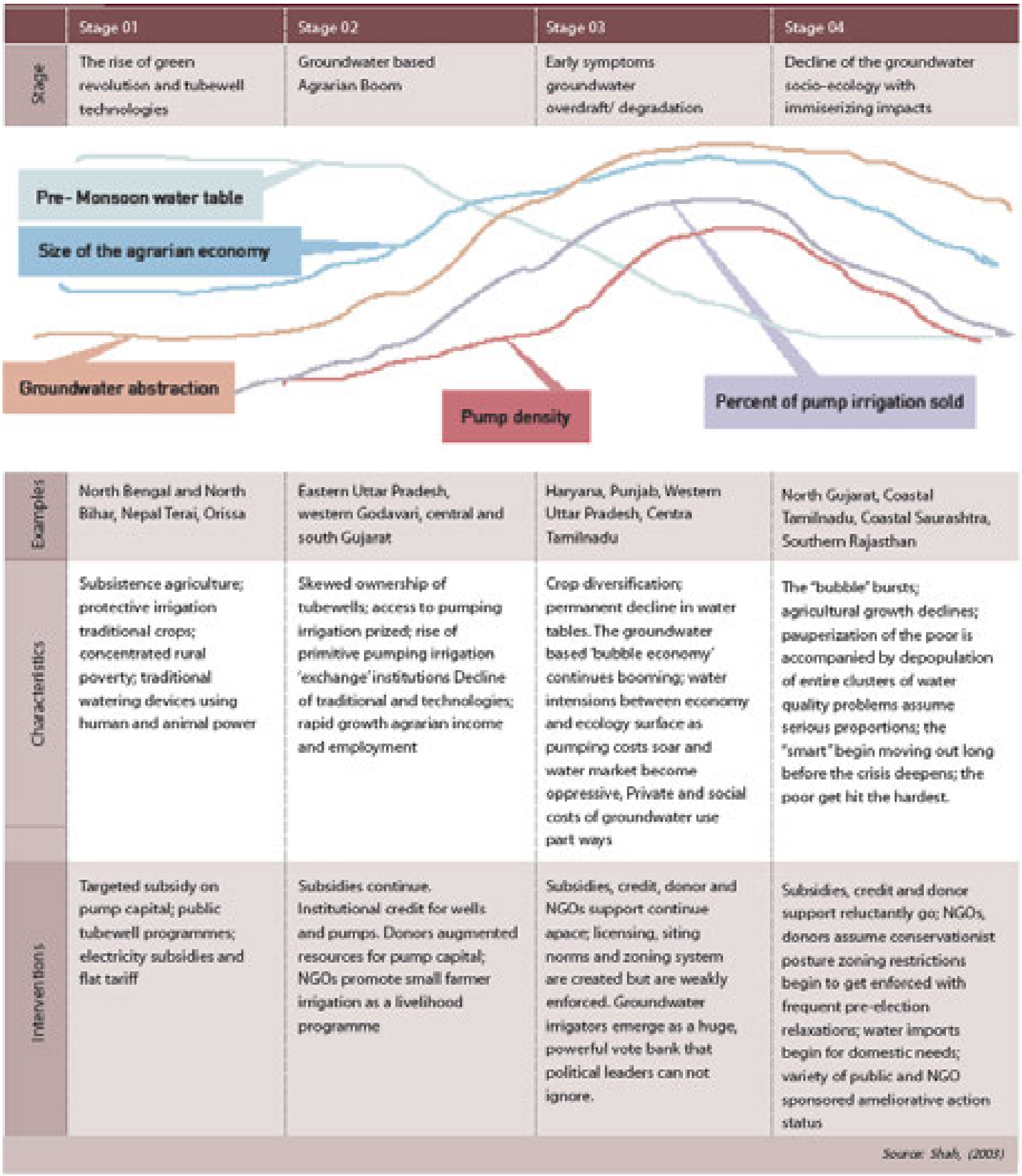
3.1 Informal models

Accounts of contemporary Informal representative organization around groundwater resources, as mechanization and demographic pressure built, are given by Van Steenbergen and Shah (2003) and Shah (2007), with more recent examples for Yemen given by Taher *et al.* (2012) and for Andhra Pradesh (Mani *et al.*, 2011) and China (Aarnoudse *et al.*, 2012). In most cases, the driver has been water scarcity. The impulse to fall into some mode of collective management has generally come late with little or no prospect of reversing trends or stabilizing aquifers. Only in the case of recharging shallow and discontinuous aquifers (e.g. Peninsular India), which experience periodic recharge to the point where they can completely fill and discharge, has this form of self-regulation offered a measure of stability from year to year, reversing trends of complete exhaustion by the end of dry years.

The scale and effect of such informal models is difficult to evaluate. There are samples of such local initiatives in many groundwater-scarce localities, and perhaps the most vivid example of the overall shape of groundwater trajectories has been given by Shah *et al.* (2003), as reported in Figure 1.

In many developing countries, governmental organizations for mitigating or otherwise addressing the impact of water scarcity have limited capacities. As a result, populations depend primarily on the resources available within communities and wider social networks. A variety of extended family and patron–client relationships exist that help individuals and families cope with the impact of water scarcity. These networks entitle members to key resources for coping, including:

- *Buffer stocks of food, water and cash.* Networks often enable people to draw on the resources accumulated by others for buffering shortfalls. This can be highly localized (e.g. sharing of resources within a joint family located within a single village) or global (e.g. diasporas - people working outside their country of origin – often supply basic resources to their home areas in times of drought or long-term water scarcity).
- *Credit*. Individuals can, at least in the short term, draw on wealthier family members, patrons or private lenders for cash, food or other forms of support when water scarcity affects agricultural production. In many cases, access to support takes the form of a loan that can be repaid in cash or kind. The terms of such loans vary considerably – from interest-free to usurious – and are often influenced by factors such as kinship and power relations within the community.
- *Alternative livelihoods*. When water scarcity affects the viability of agricultural livelihoods, individuals often rely on social networks to seek alternative livelihoods. This can involve drawing on relatives, friends or social group members who are established in other locations and livelihoods in order to obtain work. As discussed further below, migration tends to follow network affiliations – one particularly outgoing member of a group goes first and "opens the door" for others from his or her home area. It can also involve attempts by wealthy community members to initiate new forms of non-water-intensive livelihoods in their home areas. This has been a common pattern in Kutch (Gujarat) and Rajasthan, where wealthy city-based individuals start craft-development programmes in their rural home areas in order to provide income during drought periods and to develop new long-term livelihoods for rural inhabitants.
- *Risk spreading.* In agriculture, for example, sharecropping often splits the risk of crop loss between the cultivator and the land- or water-owner.
- *Diversification of income sources*. This involves families, or other communities, diversifying livelihood strategies as a group and pooling risk. Often, for example, one brother or sister will have a relatively secure job or business, while others practice agriculture and animal husbandry. Remittance income plays a critical role for many rural communities in buffering the impact of water scarcity. In addition, diversification often occurs between genders, with women staying in the villages to manage agricultural activities while men travel to cities in search of work.



	Stage 01	Stage 02	Stage 03	Stage 04
Stage	The rise of green revolution and tubewell technologies	Groundwater based Agrarian Boom	Early symptoms groundwater overdraft/ degradation	Decline of the groundwater socio-ecology with immiserizing impacts
Examples	North Bengal and North Bihar, Nepal Terai, Orissa	Eastern Uttar Pradesh, western Godavari, central and south Gujarat	Haryana, Punjab, Western Uttar Pradesh, Centra Tamilnadu	North Gujarat, Coastal Tamilnadu, Coastal Saurashtra, Southern Rajasthan
Characteristics	Subsistence agriculture; protective irrigation traditional crops; concentrated rural poverty; traditional watering devices using human and animal power	Skewed ownership of tubewells; access to pumping irrigation prized; rise of primitive pumping irrigation 'exchange' institutions Decline of traditional and technologies; rapid growth agrarian income and employment	Crop diversification; permanent decline in water tables. The groundwater based 'bubble economy' continues booming; water intensions between economy and ecology surface as pumping costs soar and water market become oppressive, Private and social costs of groundwater use part ways	The "bubble" bursts; agricultural growth declines; pauperization of the poor is accompanied by depopulation of entire clusters of water quality problems assume serious proportions; the "smart" begin moving out long before the crisis deepens; the poor get hit the hardest.
Interventions	Targeted subsidy on pump capital; public tubewell programmes; electricity subsidies and flat tariff	Subsidies continue. Institutional credit for wells and pumps. Donors augmented resources for pump capital; NGOs promote small farmer irrigation as a livelihood programme	Subsidies, credit, donor and NGOs support continue apace; licensing, siting norms and zoning system are created but are weakly enforced. Groundwater irrigators emerge as a huge, powerful vote bank that political leaders can not ignore.	Subsidies, credit and donor support reluctantly go; NGOs, donors assume conservationist posture zoning restrictions begin to get enforced with frequent pre-election relaxations; water imports begin for domestic needs; variety of public and NGO sponsored ameliorative action status

Figure 1. Rise and fall of groundwater socio-ecologies in India (after Shah et al. 2003)

While access to social networks enables implementation of the above coping strategies, such networks often impose constraints on individuals. Access and the ability to use social networks are often influenced considerably by power relations. In many traditional societies, land, labour, credit and water markets are interlocking. As a result, access to resources when they are needed in order to cope with water scarcity is often conditional on other agreements, such as willingness to supply labour or sell products at terms benefiting the creditor (Janakarajan and Moench, 2002). Furthermore, access to networks often depends on the social position of individuals. For example, gender can be a key factor influencing the ability of individuals to obtain credit or engage in risk-spreading activities, such as sharecropping (Chen, 1991). Overall, power relations within social networks are key factors determining both the relative equity with which such networks function and the *quid pro quo* position people are in when they need resources to cope with scarcity. Furthermore, as Chen (1991) comments, the ability of social networks to supply sufficient resources to cope with scarcity problems is influenced considerably by the length and severity of such problems. When problems occur over an extended period or when needs are intense, social networks enabling provision to local resources are often overwhelmed or break down (Chen, 1991). However, networks remain important in relation to migration.

3.2 Formal models

The examples of more formal arrangements driven by national or federal initiatives are not comprehensive, with the United States of America (USA), Mexico and Spain providing the bulk of the evidence. The USA experience is drawn primarily from the mid-west (Ogallala Aquifer), the southwest and the detailed examination, offered by Blomquist (1992), of small basins in southern California. Smith (2003) gives an overview of such collective approaches and assesses their performance in the light of a generally liberal approach to groundwater development. However, despite the long experience of groundwater districts in the western USA, with the exception of Blomquist, little social analysis is published and reliance on administrative/legal approaches tends to occur (Peck, 2007; Schlager 2006).The most notable experience is that gained in Mexico under the COTAS (*ComitésTécnicos de Aguas Subterráneas*), provided under the 1992 Mexican National Water Law (Wester *et al.*, 2011).The COTAS experience in the State of Guanajuato, Mexico, may not have produced the anticipated reductions in groundwater abstraction, but does illustrate how participatory mechanisms of this scale (upward of 17 000 well owners across 14 aquifers) are unlikely to advance natural resource conservation without “credible incentives for self-regulation” (Wester *et al.*, 2011). In the same vein, Lopez-Gunn (2006) questions the viability of voluntary self-regulated user associations in Spain without some form or respected or legal thrust.

An overview of available examples is given by Schlager (2007), primarily in relation to agricultural use. However, the degree to which certain forms of groundwater self-regulation are growing in urban areas remains ‘hidden’ for the reasons set out by Foster *et al.*(2012), even if examples of ‘condominium’ approaches to resolve local temporal-spatial water scarcity are striking (Barraqué *et al.*, 2012).

Several trends stand out. First, the interest of public utilities – strategic reserves and aquifer protection primarily for urban water supply, which can lead to pure groundwater-based institutions and markets. Clearly articulated definitions of conventional approaches to groundwater management are rare, and attempts to compile and evaluate approaches are limited (Sagala and Smith, 2008). Most approaches focus on direct interventions that influence either the supply of or demand for groundwater in order to create desired aquifer conditions – typically, the maintenance of specific water-level or water-quality parameters. Generally, these approaches aim at water allocation across river basins and, in doing so, generally assume the following:

a) *The presence of an organization*. An entity, whether governmental, private sector or community-based should have the capacity to affect the supply and demand for groundwater and to change groundwater quality through a combination of:

   - physical works (e.g. recharge structures, wells, surface storage, water supply and delivery technologies);
   - regulation (e.g. well spacing, licensing and use restrictions); and
   - incentives (e.g. subsidies, pricing, education, development and dissemination of technologies).

b) *Monitoring and scientific capabilities*. The presence of groundwater-level and water quality monitoring networks, along with the hydrological and other scientific capabilities, is necessary to understand and predict the impact of management actions on aquifer conditions (flow directions, water levels, and quality changes). Essential monitoring and scientific capacities for management include many of the technical factors identified in Chapter 4, such as:

   - the ability to document and monitor water use, including accurate data on well numbers, extraction rates, well locations, well ownership, etc.;
   - basic hydrogeological information on aquifers, including key boundary conditions and links with surface systems (recharge areas, locations with potential for interaction with surface streams and wetlands, water available for recharge, information on deep groundwater flows, etc.);
   - the ability to monitor conditions in aquifers through a network of monitoring wells and associated analytical capacities for water quality testing;
   - the ability to interpret groundwater monitoring data, preferably using standardized modelling tools; and

- the ability to predict, within reason, the likely impact of management actions or use changes on groundwater conditions.

c) *An enabling legal system capable of enforcing management decisions*. Because groundwater use generally occurs through private wells located on privately owned lands and because it affects livelihoods directly, attempts to manage it generally require some form of legally sanctioned enforcement authority and the establishment of a legally-recognized basis for management organizations. Unless the authority of an organization to intervene is "recognized in law", its ability to intervene in ways that affect groundwater use will be undermined by the non-cooperation of some individuals, even if the majority of people in a region support it. As a result, the legal system required for conventional approaches must incorporate:

- a legally-recognized basis for the establishment of a management organization;
- a formal and legally-recognized regulatory authority;
- a clear definition of groundwater rights (whether held privately or by the State); and
- appropriate mechanisms for dispute resolution that are viewed as legitimate by users.

d) *The presence of social – and, by extension, political – incentives to take management action at geographical and temporal scales that can affect groundwater conditions*. Most groundwater experts implicitly presume that the groundwater pollution or depletion problems should create a strong incentive for society in general, and local populations in particular, to take action. However, the research for this study suggests that this presumption is often unfounded. People do not 'care' about groundwater conditions – they 'care' about livelihoods, their economic future and many other values, often including wider environmental conditions. In many cases, the values in which people have such interests are only indirectly related to maintenance of the groundwater resource base. Even where communities or individuals are deeply concerned about groundwater problems, they face major difficulties in developing organizations that function at the scale of an aquifer or over the extended period required for management to be effective. Given the rapid changes affecting society in many parts of the world, long-term sustainability is often of far less importance to people than immediate benefits and the hope that allows for transition to better livelihoods. As a result, populations – and, by extension, their political representatives – may have strong incentives not to manage groundwater resources. At the same time, policy rarely provides the disincentives necessary to counter popular modes and mechanisms of groundwater use in order to achieve better management of the resource.

e) *The awareness and capacity at State or national levels to address cross-sectoral policy issues – such as power pricing or agricultural subsidies – that have a major impact on groundwater conditions*. In many cases, the ability of local organizations to influence groundwater use depends on State-level or national-level policies. For example, this is the case in India, where some states provide electricity free of charge for agricultural users and, as a result, reduce economic incentives to conserve water. Although this scenario is gradually changing with electricity boards opting for single-phasing (domestic supply) *versus* regulated three-phasing supply for agriculture, the actual implementation is proving difficult. However some now argue that regulation of electricity through State-level reforms has had significant impacts in Gujarat and West Bengal (Mukherji *at al.*, 2009). Therefore, conventional approaches to management require at least some ability to tailor national and State policies for other sectors in ways that influence groundwater use.

Finally, the imperatives to organize over conjunctive use in irrigation has come late in the day, even when the trends in conjunctive use had been apparent for several decades or more (e.g. South Asia). Overall, there are very few examples of institutionalization and socialization in order to play with groundwater ahead of the game – that is, the establishment of institutions for managing depletion and recharge.

3.3 A reliance on groundwater regulation

Thematic Paper 6 documents the range of regulatory approaches to groundwater management. There have been few specific summaries of the status of groundwater within national water legislation. Burchi (1999) offers a perspective based on some of the explicit mentions of groundwater made in such legislation – but this largely reflects the post-industrial concern with pollution of groundwater and aquifers. A more elaborate overview is offered in FAO (2004) in the discussion of the interface between land and water rights, while the relationship between customary and statutory rights is further explored in FAO (2005). The interest here is one of local governance and regulation of groundwater.

Observed trends in water and groundwater legislation confirm an overall preference to put groundwater in the public domain – to the extent that public registration of groundwater use is required – but as Box 2 illustrates, even when a *prima facie* case for conserving strategic aquifers exists and regulatory provision is made, actual management can be confounded by persistent 'non-compliance'.

Box 2: The Malta case

The difficulties in applying groundwater regulation do not always appear to be conditioned by the scale of the issue or the lack of knowledge. Even when the imperatives for engaging groundwater users in regulated approaches to resource management would appear straightforward and the level of aquifer understanding is high, resistance to regulation can still arise.

A recent review of the status of groundwater resources and the prospects for its regulation reveals public ignorance of, and indifference and resistance towards, public policy that would change the *status quo* for Malta's farming community. This is in spite of Malta's need to comply with the European Water Framework Directive and achieve 'good status' with respect to its groundwater resources.

Despite the declaration of groundwater protected zones in the Maltese Islands, public water supply wells are consistently compromised by "illegal" drilling, disposal of waste to groundwater, and over-abstraction from private boreholes. Intense levels of use occur across very open carbonate aquifers, most of which are in direct hydraulic connection with the Mediterranean Sea. Fresh water is available in a marginal lens floating on saline water. Freshwater is skimmed or pumped from this lens for public supply and has to be scrubbed and blended with desalinated water before it can be used as potable water.

The Maltese Resources Authority (MRA) charged with the implementation of the European Water Framework Directive has not been able to advance progressive groundwater regulation.

Source: FAO, 2006

4. Drivers of Institutional Change and the Governance Outcomes

4.1 Coping with scarcity

Groundwater scarcity appears to be the main driver of institutional response – for both formal and informal approaches. Most cases involve giving up a measure of private interest in groundwater access in order to resolve a common property problem – primarily that of water quantity and, to a lesser extent, that of water quality. What has given the impulse for social organization around aquifer management? An obvious cause might be simple demographic pressure raising the overall level of demand for water. But the actual impulse to organize in relation to specific aquifers has generally derived from a perception of scarcity: the intensive use of groundwater, as identified in Llamas and Custodio (2003), triggers a concern that the same level of service from a specific aquifer cannot be expected in the future, and hence private users become interested in different forms of community response. Without some level of private interest in a common solution, initiatives to set 'rules of the game' for a specific aquifer will not occur – even if the public interest in doing so is high. A wide range of coping responses is reviewed in Section 6.2 below.

Changes in land tenure *per se* do not appear to drive, but land tenure is fundamental if only to grant permits for drilling or digging a borehole or well. The linkage between land (held in title as a 'perfect' property right) and access to groundwater has always provided a starting point. Within agriculture there are few examples of collective linking of boreholes and transformation into a utility operation (e.g. Nile River east west delta, Egypt). For public utilities and public rural supply, in most cases, public land is implicated although competition with agricultural users on village boundaries and beyond (Chennai, India) is an issue. It is likely that private ownership will force fragmentation until the problem becomes too big to ignore.

4.2 Food security

That groundwater depletion and quality problems have serious implications for food and livelihood security in rural areas is all too apparent. However, these links are not related primarily to overall food production, but more to the income stability and reductions in agricultural risk that groundwater can provide within agricultural livelihood systems. At a macro level, current data availability and analyses are insufficient to demonstrate any direct link between emerging groundwater problems and food production at a global level. While not focused on groundwater, analyses by FAO (2002) indicate that: "the overall lesson of the historical experience, which is probably also valid for the future, seems to be that the production system has so far had the capability of responding flexibly to meet increases in demand within reasonable limits." However, this does not imply that groundwater conditions are unimportant in relation to food security. At a national level, countries such as the Syrian Arab Republic have defined domestic production as a national security issue.

More fundamentally, reliable groundwater access can provide a foundation for productive livelihood systems that enable rural populations to obtain access to education and other resources that, in turn, reduce their dependence on groundwater, the initial foundation of their wealth. The argument here is similar to that advanced by Sen and others (Dreze, Sen and Hussain, 1995; Sen, 1999) when they posit famine as a failure of entitlements – that is access to the market, governance, communication and other socio-political systems that determine the ability to purchase food when localized sources fail.

The link between groundwater and food security depends considerably on the nature of the household economy. Where households depend heavily on agriculture, groundwater provides the secure foundation for forms of production that either generate food or the income necessary to purchase food from the market. Groundwater depletion and degradation threaten this foundation and, thereby, threaten food security, primarily where populations have few options other than to retain their dependence on agriculture. From this perspective, doing nothing to address emerging groundwater problems could have major implications for food security at national or global levels as the prime buffers against variable rainfall become progressively depleted and degraded.

4.3 Social stability

Groundwater-based agriculture can provide a foundation for locally-based economies that alleviate poverty and help to root populations in areas where core educational and other services can be developed. This appears to have been a consideration in Saudi Arabia when groundwater development was used to catalyse wheat production. To limit urban migration and stabilize rural populations, Saudi Arabia drilled more than 100 000 wells, provided a 40-percent subsidy for farm equipment, and put in place a price-support policy for wheat between 1980 and 2000 that ranged from USD 0.57 to USD 0.97/kg. Abderrahman (2001) concluded: "This agricultural development was an essential tool for social balance between urban and rural areas. The intensive agricultural developments resulted in the creation of stable farming communities in rural areas…. These prosperous communities helped in supplying the country with educated healthy generations of young men…They also helped in filling the deserted areas and in giving the support to security and defence authorities in remote areas…Other benefits were gained also such as minimization of movement of inhabitants from rural to urban areas."

The use of water as a tool for stabilizing populations is not unique to Saudi Arabia. In many countries, agricultural intensification based on groundwater development has been a leading element in agricultural development and poverty alleviation strategies. This was the case in India and, as recently as 1995, it was proposed as a lead strategy for Nepal (Agricultural Projects Services Centre and John Mellor Associates, 1995).Groundwater overdraft, combined with drought, undermines agricultural production and is a factor catalysing outmigration. For example, this has been well documented in field research on drought in Rajasthan and Gujarat, India (Moench and Dixit, 2004). Effective groundwater management can, at least to some extent, reverse this. For example, in Andhra Pradesh, India, out-migration has halted, and populations are migrating into regions where aquifer management has proved viable. Prior to this, outmigration in years of poor monsoon had become pronounced (APFAMGS, 2006).

4.4 Technology

As detailed in Thematic Paper 8, access to technology and energy will continue to dominate and entrench self-supply under 'liberal' conditions that do, in fact, prevail in most countries with respect to groundwater. The adoption of improved technology and the distribution of energy can be expected to permit the progressive extension of capture of groundwater. This may reflect an overall inability to regulate thousands of individual users or a deliberate policy of rural subsidy. The degree to which local groundwater institutions organize around specific types of technology is revealing. For instance, van Steenbergen *et al.* (2003) point to the role of common ownership of step-down transformers in Andhra Pradesh, India, and the evolution of groundwater 'utilities' with shared pump and distribution technologies in Egypt.

4.5 Groundwater markets

4.5.1 Informal markets

Informal groundwater markets have conferred a distinct level of local organization and a measure of self-regulation, as the demand for groundwater to service both agriculture and potable water supply has grown in Asia (Shah *et al.*, 2003). By their nature, markets are flexible institutions that enable reallocation of water as demand and availability change. Informal water markets, in urban areas, have evolved as a way of coping with poor quality by averting impacts on domestic consumers. Informal groundwater markets are also common in regions, such as in India, where groundwater plays a major role in agricultural production. In many ways, the evolution of such markets can be seen as a mechanism for coping with scarcity and the cost of obtaining supplies. Where groundwater is readily available close to the surface and the cost of wells is, as a result, low, there is little incentive for landowners to buy or sell water. Where water is scarce, in either an absolute sense or because the costs of wells and pumping are significant in relation to farm incomes, then strong incentives often exist for the evolution of local, informal groundwater markets.

Evidence on the role informal water markets play as an institution for coping with water scarcity is mixed. The situation that was discussed above, in locations such as Yemen and Chennai and Ahmedabad in India, indicates the major role that informal water markets can play in reallocating available supplies from agriculture to uses where domestic or industrial consumers have more ability to pay. In such situations, water sales can represent a major source of livelihood for well owners while also meeting the basic needs of domestic consumers.

Box 3 The implicit water markets of the Kolwan Valley

In the Kolwan Valley of the Mulshi Block of western Maharashtra, India, there is little evidence of water trade between farmers. It has 16 villages, forming part of the landscape of the Western Ghat. Paddy is grown in the monsoon as the rainfall is high (1 600 mm), and crops such as wheat and vegetables are cultivated in winter. Some farmers also grown sugar cane. In the dry season, irrigation is through some 100 lifts from the main channel of the river, fed mainly by releases from three upstream reservoirs. Groundwater is used mainly for drinking-water supply but also as a supplementary source of irrigation to the lift schemes. During the course of the AGRAR Project (Kulkarni *et al*., 2005; Gale *et al*., 2006), formal questionnaires revealed that there was no water sharing or trading between farmers. However, subsequent surveys revealed that there was a gap of more than 50 percent between the amount of irrigated land and the quantity of water supplied through the lift irrigation system. Groundwater use was also estimated, and the gap came down to about 40 percent. More probing investigations and field studies revealed that a significant part of the irrigation in the valley was on farms that had no "formal" access to any irrigation source. Farmers in most villages subsequently conceded that there was a trade between farmers with access to surface water and those without. This was essential in order to make sure that they would be able to grow at least the minimum share of the crop that contributed to a major share of their agricultural livelihood. It seems that water markets can exist, even in areas where they do not appear to.

Source: Kulkarni *et al*., 2005; Gale *et al*., 2006.

However, water sales appear to be less common in situations where well yields are low and groundwater access is unreliable, than in situations where water availability is higher. For example, research in Tamil Nadu, India, indicates that farmers only sell supplies that are in excess of amounts they need to irrigate their own crops (Janakarajan, 1994 and 1999; Janakarajan and Moench, 2002). Water markets in Gujarat, India, have developed in deep aquifer areas. There, although water levels in the deep alluvial areas are declining at rates of 1-3 m/year, well yields are high, and the amount that can be pumped is more than sufficient to irrigate the land held by most individual farmers. Because water levels have declined substantially, the fixed costs of drilling a well are high. Pumping costs are also substantial, and they are also fixed, because electricity is charged as a flat annual fee based on pump horsepower rather than on consumption. In this situation, the high fixed costs associated with groundwater irrigation, combined with the productive nature of the wells, create a strong incentive for farmers to sell excess supplies. The marginal cost of pumping is zero, and the average cost declines with the amount pumped (Moench, 1993 and 1994; Shah, 1993).

Research in recent decades suggests that the evolution of informal water markets, as a mechanism for allocating available supplies and coping with scarcity, appears to depend on a variety of factors: (i) Hydrology, particularly as it affects well yields, is important. Informal water markets within agriculture are unlikely to evolve if the supplies available from individual wells are insufficient for irrigating the average landholding; (ii) Transport is also a critical factor. In Ta'iz (Yemen), Kathmandu (Nepal), Chennai and Delhi (India), proximity to roads and demand centres is critical to the economic viability of tanker markets; (iii) Cultural characteristics, in particular traditions of cooperation, may also be important. For example, in Gujarat, the Patel community has strong cooperative traditions that enable farmers to easily lay pipelines under one another's fields and to form cooperative groups for managing wells – activities that can be socially complex in other cultural environments. Such cooperative arrangements also appear to provide a foundation for relatively equitable water markets; (iv) Trust is generally high, and exchange agreements are honoured. In other situations, cultural traditions of cooperation are not as widespread, and the social basis for water markets to function may be weaker. Further, as discussed above, informal water markets are often interlinked with credit, labour and produce markets, and are influenced considerably by social power relations at a local level (Janakarajan, 1994; Dubash, 2000). Consequently, while they may help sections of the population cope with water scarcity, other sections may be affected adversely by their operation.

4.5.2 Formal markets

Beyond informal water markets, much has been written on the role that more formalized water markets based on clearly defined rights systems can play in enabling water reallocation in times of scarcity. In the west of the USA, such rights systems have introduced substantial flexibility into existing water allocation patterns. This has played a significant role in the ability of regional agricultural economies and municipal areas to cope with fluctuations in water availability between years. As a result, water markets along the lines of those developed in western USA are often proposed as mechanisms for increasing the efficiency of water use and flexibility of water allocation in other areas. At the same time, the evolution of water markets in these areas was supported not only by the rights system, but also by good scientific data and a continuously evolving water law framework.

While attempts have been made to develop water rights systems and market mechanisms in other areas, e.g. Chile, the results have been mixed (Bauer, 1997). Furthermore, particularly in the case of groundwater where data for the establishment of rights systems are often unavailable, how water rights systems could be established is an open question. Debates over the establishment of water rights systems have been widespread in India but have led to little real movement (Moench, 1994 and 1995). The *Pani Panchayats* in Maharashtra set forth delinking land and water rights for equitable distribution of water, both in small surface water reservoirs as well as in the basalt aquifers from low-rainfall, drought prone regions. Progressively though, many of these were impacted by free-riding resulting from large-scale well-programmes, rural electrification and other such factors (COMMAN, 2005; Kulkarni *et al*, 2009). In the absence of a right-based legal framework, that India is now attempting to revisit (Cullet, 2012), many efforts at linking rights and allocations through informal, socially-driven efforts seem to be running into many different types of hurdles. In Mexico, the process of registering all wells as a precursor to the establishment of rights has, as previously discussed, been problematic. Finally, in the west of the USA, where volumetric right systems have been established, it has proved difficult to limit groundwater extraction to sustainable levels, and substantial debate exists over the impacts of water markets on third-party and environmental interests. As a result, major questions remain over the role that water markets could play as an adaptive mechanism for coping with changes in water availability and demand.

4.5.3 Synthesis: Issues in the Role of Water Markets

Water markets represent another form of institution for allocating available supplies. Key issues in the role that markets play as part of coping strategies include:

a) *Short-term* versus *long-term impacts.* In locations such as Gujarat and other states in India, informal water markets enable access to "secure" water supplies in drought periods, but they also contribute to overdraft because rights systems bear no relation to the volume available on a sustainable basis. As a result, while they are effective for coping with short-term fluctuations in water availability, they undermine the resource base available for coping in the long term.
b) *Social differentiation.* Groundwater access is influenced considerably by landownership and well-ownership patterns. While water markets enable reallocation of available supplies, they do not reflect third-party interests – such as the interests of agricultural labourers. The trade-offs inherent in existing informal water markets need to be understood more fully. In order to evaluate the role of water markets as a coping mechanism it is, for example, important to know how many livelihoods are being created *versus* how many lost in situations such as those in Tamil Nadu, India, and Ta'iz, Yemen.
c) *Transition from informal to formal.* Informal groundwater markets are common in many areas, but relying on these as a major mechanism for reallocating available supplies in the absence of clearly accepted rights systems has major equity implications. Establishment of such formal rights systems is, however, culturally complex and often requires data that are unavailable.

Overall, while the evolution of markets as a mechanism for coping with water scarcity is common, the operation of water markets has complex implications within local societies. In many cases, informal markets can help populations to cope with short-term fluctuations in water availability. However, because they do little to address (and may exacerbate) overall resource-use imbalances, they may exacerbate long-term water scarcity problems. In theory, markets based on quantified and transferable water rights systems could serve as a highly flexible mechanism for coping with both long-term and short-term fluctuations in water availability – but the establishment of rights systems is complex. Questions of transition between the development of markets as an informal coping response to scarcity and as a formal "institutionalized" response are particularly important.

4.6 Environmental compliance

Finally, environmental compliance and aquifer protection appears weak as a driver of collective management. The impact of groundwater depletion and quality problems on streams and wetlands has been extensively documented in many parts of the world (Sophocleous, 2002a). In India, concerns over the impact of falling water levels on stream flows began to emerge more than two decades ago (Bandara, 1977; Kahnert and Levine,1989). Groundwater and surface water systems are often closely interconnected. Wetlands and base flows in rivers generally depend on groundwater contributions. As a result, even relatively minor changes in water levels can have a major impact on key environmental values (Burke and Moench, 2000). However, the issue is not related only to water availability. Changes in groundwater quality can also have a major impact on surface ecosystems. In many developing countries, including India, the significance of groundwater in maintaining base flows and wetlands is something that has begun to be understood and accepted only in the last decade or so.

Concerning the question of how widespread the impact of groundwater development is on wetlands and streamflows, the National River Authority in the United Kingdom (UK) “has drawn up a priority list of 40 locations where unacceptably low river flows are considered to be caused by excessive authorised abstractions, rather than drought” (UK Groundwater Forum, 1995). Between the 1960s and 1990s, perennial streams in Kansas, USA, decreased in length in the western third of the state, altering the composition of riverine communities considerably (Sophocleous, 2002a and 2002b). Stream and groundwater quality has also declined with saline migration and the introduction of nutrients from agricultural activities into aquifers that feed surface systems. In the USA, more than 48 per cent of the original wetland areas have been lost on average in all of the States (Gleick, 1993). Some States have seen larger declines. For example, in California, wetland areas have declined from historical levels of 1.2-2.0 million ha to perhaps 182 000 ha, a drop of 85-90 per cent (DWR, 1994). The loss of inland freshwater wetlands is also severe in Europe with losses of 60-70 per cent in several countries (Sophocleous, 2002b). While some of these losses have been caused by changes in land use and intentional drainage programmes, intensive extraction of groundwater for multiple uses is increasingly well documented as a major causal factor. Overall, the impacts of intensive groundwater use on key environmental values have been estimated as significant and the costs of doing nothing as substantial.

Integrated approaches to groundwater management are conceptually logical but, as suggested above, extremely difficult to implement in practice. This is particularly true under developing-country conditions, where many issues of direct and fundamental importance to survival and livelihoods place large demands on limited financial and technical capital. This could depend on a combination of fundamental factors in the way people organize along with challenges, such as the scale of management needs, data availability and variability that are more groundwater-specific.

Part 2 Diagnostic

5. Constraints

If an environment of good conduct is to be extended to fill the apparent groundwater governance gaps, the need for this to apply at the point of abstraction or the point of pollution will always implicate local institutions who have an interest in maintaining public goods (e.g. water supply or specific common property resources such as pasture and aquifers). Three constraints stand out: First, the local and private nature of many groundwater economies in rural and urban settings stands out as a main constraint – and sometimes as an absolute barrier. The preference for assured private supply from groundwater sources are intense in rural and agricultural settings – but has a relatively recent legacy as cheap hand-pumps and energized pumps have become available. This essentially private nature of informal groundwater economies appears to have confounded attempts at direct regulation of groundwater use – whether to prevent use of polluted groundwater, protect local sources or curb what are regarded as excessive drawdowns.

Second, the rigidity of water management institutions with respect to groundwater and hydrocratic visions is notable and persistent. In the case of groundwater, the ability to implement integrated management concepts is further limited by a combination of factors including:

- *Data, information and technical understanding*. In most cases, data and technical understanding are rarely sufficient for effective management of groundwater systems, let alone integrated management.
- *Scale, numbers, geography and time*. Larger aquifer systems often extend under hundreds of villages containing thousands of users, and the geography of groundwater rarely matches the geography of human administrative systems.
- *Variability*. Aquifer conditions vary considerably even at a micro-level, as do social and economic conditions. This variability complicates the development of management systems by making uniform, rigid and often "prescriptive" approaches inappropriate.
- *Social capacity constraints*. In many areas, the social capacity available for management is limited. Either organizations do not exist, financial and other capital requirements are unavailable, or human resources are already fully committed.
- *Persistence of conventional 'water-focused' approaches*. In the groundwater case, this is even more evident as they tend to be very groundwater-focused. They are intended to reduce social and environmental impacts of intensive groundwater use by controlling changes in groundwater resource conditions. It can be argued that this focus misses many opportunities present in the wider socio-economic and political context for mitigating the impact of groundwater overdevelopment on key environmental or social services.

The limitations identified in this section lead into subsequent arguments for the development of a wider policy perspective. The above elements can be seen as the foundation for conventional approaches to groundwater management. However, it is important to recognize that, on a conceptual level, the water management community generally locates groundwater issues within larger concepts of integrated water resource management (IWRM) and sees groundwater as best approached as part of an IWRM package. However, definitions of IWRM are broad. The Global Water Partnership (GWP) (CGWB, 1995; GWP Technical Advisory Committee, 2000) states that: "IWRM is a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."

The definition is demanding. It requires development and maintenance of a process that is capable of addressing a wide variety of land-use as well as water issues in order to meet multiple, and often contradictory, economic, social and environmental objectives across multiple physical and administrative geographic scales.

Despite their complexity, IWRM concepts are the driving force behind most 'conventional' attempts to address the wide variety of water management needs. This implies that the requirements identified above as central to conventional groundwater management are only a starting point. Additional capacities are required if groundwater issues are to be addressed as part of a comprehensive IWRM approach. They range from an ability to understand and monitor the wide variety of factors that influence land as well as water use to social psychology and the ability of management entities to work closely with a wide variety of stakeholders across multiple temporal and geographical scales.

Finally, there is limited institutional interest attached to highly-distributed low-intensity investments. Integration necessarily involves a set of transaction costs and can be expensive. While it may be possible to concentrate available social capital to implement management in a few high-priority areas, resources are often insufficient to implement management on large space and time scales. Moreover, the amount of capital required increases as resource conditions deteriorate, the scale of a problem emerges to be much larger than anticipated and the social capacity constraints become evident over time.

5.1 Principles versus practice: the limits of human organization

As just explained, IWRM involves the development of processes and organizations to promote "the coordinated development and management of water, land and related resources" (GWP Technical Advisory Committee, 2000). Such organizations require foresight and the ability to understand and address multiple, often conflicting, debated and vague objectives over long periods. This seems to contrast with the nature of most human organizations. This paper finds that organizations tend to be most efficient and effective when they focus on clear tasks and immediate needs. Long-term objectives may be addressed – but only where the objectives are very clearly and narrowly defined in ways that draw support across broad sections of the population. It is necessary to examine what supports this assertion and what it means for integrated approaches to groundwater management.

The clear definition of long-term objectives largely depends on political priorities and financial processes. Leadership that is capable of providing high levels of support over the long periods required for sustained management of the water resource base is extremely rare. Leaders are often occupied by the issues of the day and have to devote most of their attention to such issues. As a result, support at a political level for the broad types of actions necessary to achieve IWRM will vary considerably over time. Limitations on support at the political level are further complicated by the array of social, technical, institutional and economic capacities required in order for integrated approaches to succeed. It suggests that organizations will probably be most successful when their focus revolves around a relatively narrow set of clearly-defined activities. Building core competencies in the diverse set of fields required for integrated approaches to succeed is at best a complex, long-term process. In many situations, the absence of sustained funding and other support may make it, for all intents and purposes, nearly impossible. Hence, management organizations focus on immediate problems rather than on a wider (and generally much more nebulous) set of objectives. As problems are addressed, attention shifts to new areas, both geographically and in terms of the types of problems itself. Responses to problems tend to be incremental rather than comprehensive (Moench, 1999a).

Water experts often decry the lack of "political will" as a major factor undermining groundwater and surface water management. As the GWP Technical Advisory Committee (2000) comments: "in many cases, the biggest problem is not lack of adequate legislation but lack of the political will, resources and means to enforce existing legislation." In the case of groundwater, the partial visibility and the largely hidden nature of the resource make the task of separating demand, supply and need difficult (Kakade *et al*., 2001).The emphasis on focus made in business literature is replicated in the literature on the management of common-property resources such as groundwater. This literature highlights an array of factors that research has indicated to be common to successful management of common-pool resources (BOSTID, 1986; Bromley, 1998; Ostrom, 1992 and 1993).

Some of the most important factors that emerge regularly in this literature include:

- articulation of the need for groundwater management;
- clear systems of rights or rules-in-use governing access and resource utilization;
- clear boundaries on the resource and the user group;
- mechanisms to control free riders (including ways to restrict access for non-members or those not holding resource-use rights);
- clear systems for monitoring resource condition and use, including documentation of the benefits from management;
- relative economic and cultural homogeneity among group members;

- a proportional equivalence between the costs and benefits from management;
- effective mechanisms for enforcement;
- small primary-management group size, often accompanied by the nesting of institutions where some management functions need to occur at regional or system rather than local scales[1].

Taken together, all of the factors discussed above point towards fundamental social organizational challenges facing the development of comprehensive integrated approaches to groundwater management. While logical from a resource perspective, such approaches do not match the way humans organize. Human society worldwide has faced major problems in responding to "creeping environmental problems" (Glantz, 1999) such as those associated with groundwater. Writing on the underlying structural changes at the root of revolutions, Holling, Gunderson and Peterson (2002) comment that: "organizations and institutions failed to cope with these slow changes because either the changes were invisible to them, or they were so contested that no action could be agreed upon." The same could be said about groundwater: when cast in a "comprehensive, integrated" framework, management objectives are generally too diffuse, boundaries are unclear, too many people, needs and objectives must be involved, and so on. Broad integrated attempts at comprehensive groundwater management are unlikely to succeed in many contexts. These arguments are elaborated on in Moench (2002). They point to the need to focus groundwater management attempts narrowly – on clearly defined problems that are of direct relevance to local populations.

5.2 The risks in doing nothing

The risks associated with the intensive use of groundwater resources are illustrative of two issues:

1) the potentially large social and environmental consequences associated with unregulated intensive groundwater development; and
2) the lack of detailed information for evaluating the actual social and environmental impacts emerging in many areas and the extent to which they represent real problems that society cannot afford to ignore.

Morris *et al*. (2003) have documented how falling water levels and water quality degradation, associated with intensive groundwater development, have significant implications for surface ecosystems, particularly wetlands, in-stream flows and water quality. Implications for basic livelihoods, poverty and social stability have the potential to be equally severe – but are far less well documented. Further, unlike environmental values, which depend directly on groundwater levels or water quality, social impacts are contingent on a wide variety of factors unrelated to groundwater resource conditions. For example, the most severe impacts of water-level declines will probably emerge where drought affects regions with shallow, poorly diversified economies with large populations that depend directly on agriculture for their livelihoods. In this situation, people may not have the ability to diversify livelihood strategies and move beyond, or otherwise cope with, the lack of water for agriculture. However, in other situations, the depth of regional economies may enable farmers to diversify livelihood strategies and escape from dependence on agriculture – effectively mitigating the impact of changing groundwater conditions on livelihoods.

Differences in these scenarios point to the complexity of evaluating the larger significance of groundwater-level declines. At one extreme, groundwater overdraft can catalyse local food insecurity, migration and political instability. At the other extreme, intensive and unsustainable use of groundwater can be a mechanism enabling regions to escape from poverty to far more diversified and wealthy livelihoods. The main risk to society lies in not knowing which track it is on in different locations and, as a result, in the inability to develop appropriate and targeted response strategies.

Uncertainty and risk are also at the centre of macro questions about food security. While current analyses suggest that groundwater overdraft has little implication for global food production, this result depends on the assumption that climate and weather changes will not cause droughts to occur simultaneously across large food-producing regions of the world. Groundwater is the primary buffer for agriculture against drought – and simultaneous droughts in major food-producing regions, while unlikely, could have a major impact on food

[1]This follows from Olson (1965): "unless the number of individuals is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, rational, self-interested individuals will not act to achieve the common or group interests."

production unless groundwater remains available as a buffer. However, beyond this, food security is influenced considerably by livelihoods and the functioning of markets and global distribution systems. By buffering local production systems and the agricultural livelihoods that depend on them, groundwater provides insurance against disruptions in regional and global market and food transportation systems. In arid regions, groundwater overdraft can eliminate this insurance and, as a result, increase the vulnerability of populations to food insecurity. Many countries in the Near East and North Africa have major programmes to promote domestic food self-sufficiency because of fears that food could be used as a weapon or that supplies could be disrupted in the case of regional conflicts. In this case, overdraft may undermine the security they are seeking.

All of the above points to the importance of information and improved understanding as a basis for developing effective responses to emerging issues. The risks involved in doing nothing – or in doing the wrong thing – in response to declines in groundwater levels and quality are potentially huge. As a result, the presence of complexity and uncertainty should not become an excuse for inaction.

5.3 What 'should' be done as opposed to what 'can' be done

This Thematic Paper has indicated a fundamental divergence between the ideals of 'comprehensive' and 'integrated' approaches to groundwater management and the reality in groundwater dependent economies. At the same time, it has highlighted the fundamental social and environmental costs of doing nothing. Clearly, allowing emerging problems to simply compound is not a desirable outcome. However, the distinction between what 'should' and what 'can' be achieved is fundamental. This analysis suggests that conventional approaches to groundwater management will probably only succeed under a relatively limited set of conditions. Although the conditions listed below are not comprehensive, they would include locations where:

- the need for management is clear and widely recognized by both policy-makers and local users;
- the aquifer has a clear strategic value for key uses, such as urban supply or the maintenance of wetlands and in-stream flows, where public "demand" for management is strong;
- sufficient data on aquifer conditions are available to create a recognized common basis for management;
- there are clear technical options for management, and these options do not require substantial sacrifices for large and politically influential portions of the population;
- social, economic and hydrological conditions are sufficiently stable that management can produce clear benefits rapidly.

6. Local Groundwater Institutions and the Scope for Securing Economic, Social and Environmental Benefits through Governance

Is there enough institutional scope to secure both livelihood and environmental benefits or will they be mutually exclusive? What are the types of social changes and mechanisms for coping with water scarcity and water-related problems that are already occurring and which could serve as entry points for more explicitly adaptive strategies? One avenue of direct application has come from leading with groundwater information and the generation of knowledge and practice within self-organized communities. Arguably, this has turned around the livelihoods prospects in parts of Andhra Pradesh, India (World Bank, 2010). A groundwater management platform was also able to promote Integrated Pest Management (IPM) and the use of organic fertilisers (including vermiculture) to avoid the use of expensive inorganic fertilisers and harmful pesticides.

Thematic Paper 8 has highlighted the role of both technology and the linkage with energy management as specific sets of drivers that result in specific patterns of use, but also opportunities in resource conservation. And Thematic Paper 6 has indicated that more groundwater regulation can be expected, but that it may be better to anticipate and avoid formal regulation through forms of autonomous adaptation. Taken together, these findings and conclusions suggest that long-term benefits can be secured if local institutions are given the policy space to operate. In many ways, this implies that potential instruments of governance that operate through more centralised systems may need to be decentralised significantly in order to adapt to the realities of groundwater conditions and contexts. The opportunities for doing so are discussed in this Section.

6.1 Opening up management perspectives

Conventional water-focused approaches to groundwater management represent only a portion of the policy and institutional space that is available for responding to emerging problems. Many of the impacts associated with emerging groundwater problems depend on a much wider array of social and economic conditions. Consequently, adaptive interventions that affect those wider conditions may be as important for mitigating the impact of groundwater depletion or degradation as those directly affecting the groundwater resource base itself. Approaches which are directed at controlling the resource base and its use may, in fact, have limited application in effecting groundwater resource management.

At the other end of the spectrum lies the relatively unexplored policy space of adaptation. It is this space that requires greater attention, given the rates at which groundwater is being developed and the anticipated impacts of climate change.

Conceptually, three broad, complementary and often overlapping sets of 'adaptive' strategies are possible for responding to the limitations associated with the more conventional or direct management strategies discussed. These are:

- *Incremental approaches to groundwater management.* Strategies are adjusted continuously as new information emerges or conditions change.
- *Indirect management strategies.* Strategies that emphasize opportunities for influencing groundwater use by shaping the context in which groundwater use occurs. They include strategies, such as power pricing, that are part of many conventional management strategies. However, they also include power rationing and potential opportunities for shaping groundwater use through high-level policy and economic changes (such as crop price supports).
- *Specific adjustment to groundwater conditions.* Strategies that emphasize opportunities for adapting social and economic systems to groundwater conditions and dynamics rather than the other way around. These strategies take groundwater conditions as largely given and seek to identify opportunities for reducing or mitigating problems through changing the social and economic context of use.

All three of the above sets of strategies start from the recognition that demand for water is socially constructed. Societies, in general, have little interest in the actual state of groundwater resources, but tend to have very high levels of interest in the environmental, social and economic services associated with groundwater when it is left *in situ* or extracted for a specific use. The instrumental value of groundwater derives very much from the utility as a highly distributed on-demand service. But if management focuses on regulating the service, by for instance, imposing caps on borehole drilling, the distributed access advantage may be lost. It may make better hydraulic and productivity sense to exploit an aquifer with many boreholes pumping at low rates than just a few pumping intensively, although many such decisions would also depend upon the aquifer typology in a region.

At present, groundwater management focuses on the groundwater '"means'" by which services are produced rather than on the '"ends'" – the productive outcomes of use. The implicit goal is to manage groundwater or groundwater use in ways that enable existing services to be produced on a sustainable basis. In some cases – particularly where economies have developed based on intensive agriculture and mined groundwater – this objective is extremely difficult to achieve. In other cases, changes in the way local populations are adapting, or could adapt, to meet fundamental livelihood objectives contain opportunities for addressing or mitigating groundwater problems. In Gujarat, India, farmers often respond to discussions over declining water levels by pointing out that the income they generate through unsustainable groundwater use is enabling their children to obtain an education and develop non-farm (often urban) livelihoods. In many regions of the world, the first response to falling water levels is simply "how can we add more water to what is underneath" rather than "can we use less groundwater and obtain the same produce". Although the possibility of managing demand for groundwater exists, it is not an easy task.

At the same time, urban-based economic opportunities are perceived to be increasing, and many people aspire to urban lifestyles even if the reality of urban life is different from what they envision (UNFPA, 2007). A social transition is occurring that will re-shape groundwater demand in fundamental ways whatever attempts managers may make to control resource use directly. In many locations, the livelihoods of local populations are already shifting. In parts of India, for example, the pull associated with growing opportunities in the non-farm sector and in urbanizing areas is, for many, a major reason for moving out of agriculture. This pull often operates in conjunction with the evident limitations facing farmers in arid areas where water levels are falling. Farmers generally understand fully the implications of declining groundwater levels for future agricultural prospects, and they are using the capital generated through intensive but unsustainable irrigation to educate their children and develop businesses that will ultimately enable them to move beyond dependence on agriculture for their livelihoods. Perhaps, such changes offers opportunities to address challenges in understanding and managing groundwater resources through somewhat unconventional ways including smarter investments in decentralised groundwater regulation and governance.

6.2 Adapting for change

Coping with the conjunction between long- and short-term changes in water availability is particularly relevant in relation to groundwater use and protection. In most cases, systemic changes in groundwater availability are gradual and appear in the long term. Water-level and quality declines rarely occur "suddenly". Instead, trends emerge over periods of years or decades. However, crises are likely to occur when long-term systemic changes are overlain by either short-term seasonal fluctuations in water availability or, more importantly, droughts of several years' duration (Moench, 1992; Moench and Dixit, 2004).

Little research has been conducted on the strategies that communities use to cope when long- and short-term processes coincide, and little evidence has been gathered to suggest that communities have developed effective strategies for coping with the combination of short- and long-term changes to aquifer state and groundwater quality. Most coping responses to short-term and relatively well-anticipated disruptions in water supply fall into five broad categories:

- *Control: eliminate or reduce variability through increases in storage (reservoirs and ponds) or source diversification.* This strategy at both an individual and societal level has been a major factor driving the development of groundwater in locations such as India.
- *Spread risk through diversification: spread risk to reduce impact of water scarcity on overall livelihood equation.* It can be done through established institutions for risk spreading – i.e. insurance companies –, diversification of livelihood strategies and dependence on social networks. At household, business and community level, diversification into non-farm livelihoods (government, business and migration-based) is one of the most common responses to climate variability.
- *Adjust or adapt: plan activities to reflect or accommodate anticipated fluctuations in water availability.* Seasonal changes in cropping patterns to take advantage of periods when rainfall can be anticipated or migrating during dry periods are typical examples of this type of coping strategy.

- *Mitigate: buffer (draw on savings or other forms of capital) or reallocate available supplies, through water markets or other mechanisms, so that the economic value of production is maintained despite the impact of water scarcity on "normal" activities.* Buffering strategies can themselves be risky – for example, buffering the impact of drought can translate into depletion of capital assets, if water supply disruptions are more severe or longer term than anticipated. Where seasonal variability in water availability is high, as in most of South Asia, the evolution of water markets and other mechanisms for flexible reallocation of supplies is a common adaptive response that enables reallocation of water on a short-term basis. In effect, reallocation can mitigate the economic impact of drought by enabling production mixes (of crops or non-agricultural activities) that maintain income levels while using less water.
- *Avert: change activities in ways that, in effect, reduce scarcity.* Scarcity is a relative concept that is only relevant in relation to demand. When people anticipate scarcity, they often take actions that, in effect, change the demand for water and, thus, eliminate scarcity. Diversification of livelihood strategies – in some cases based on long-term migration – is a prime example of averting behaviour. Averting is different from the implementation of adjusting or short-term migration activities that focus water demand on periods when availability is greater.

6.2.1 Building on household user-level coping strategies

In most cases, populations use a mix of the above strategies in order to cope with short-term fluctuations in water availability. The rapid spread of groundwater development can be seen as a first-order coping strategy where control – the ability to reduce water supply variability – was a major motivation for farmers to invest in wells and equipment. Reductions in variability translate directly into increased production and income (Moench, 2001). In many situations, the stabilization value of groundwater – i.e. the value of reductions in variability as opposed to the water *per se* – is approximately equivalent to the value of the water itself (Tsur, 1990 and 1993). In addition to groundwater development, supply-side coping strategies are a common response to short-term fluctuations in water availability. For example, this is the case with "water harvesting", a strategy that plays a central role in India's approach to "drought-proofing" and rural development. Such water harvesting strategies have traditionally been common in many communities (Agarwal and Narain, 1997), and they are now the focus of major government programmes. In some situations, they are being advocated as a panacea for addressing water scarcity caused by a combination of groundwater overdraft and drought.

Local populations supplement supply-side control initiatives such as the above, with a wide array of other coping strategies in response to seasonal droughts or water deficits. At the household level, research in India by Chen (1991) documents that: "in coping with seasonality, most households attempt to protect themselves from short-term reverses in income and subsistence flows. Adapting or diversifying normal activities, building up or drawing down inventories, seeking employment, share-cropping land, borrowing for consumption or production and migrating for employment are all common ways of dealing with the risks and uncertainties associated with seasonality. For additional support, households turn to family, kin and caste neighbours or draw upon common property resources. When all else fails, households are forced to mortgage or sell assets."

As Chen (1991) comments: "the above types of coping strategies historically had strong institutional foundations in patron-client relations, local rights structures at the community and village level, and caste, kin and family relations. These supporting institutions are now, however, all eroding to some degree." Such institutions were originally a core part of local community structures. Now, place-based community structures are often changing in fundamental ways as the multifaceted process of globalization, and demographic change alters the larger social context in which they were originally embedded.

It is important to recognize that many of the household strategies for responding to short-term water scarcity are not focused on controlling the variability of water supplies *per se*. Instead, they emphasize adjustment, mitigation and averting. Share-cropping spreads risk, it mitigates the impact of scarcity on individual farm households by splitting the impact of crop losses between the farmer and the landowner. It also enables adjustments such as intensification of activities in relation to the most limited resource. Within farms, research in *warabundi* systems – surface irrigation systems in India in which water is delivered to areas on a rotational basis – indicates that farmers often respond to scarcity with deficit irrigation practices. They also reduce risks from uncertainty in the availability of water supplies by reducing cropped areas to a level where the supply of water is virtually guaranteed to avoid crop failure and by intensifying cropping on that portion (Perry and Narayanamurthy, 1998). Similarly, in fieldwork in large parts of India and mainly in the States of Gujarat and

Maharashtra, farmers often crop areas immediately adjacent to wells and share the products based not on landownership but on shared rights in the well.

Risk spreading also occurs through crop diversification (i.e. planting a variety of crops with different durations and water needs) and diversification of income sources. This is a common strategy for coping with risks and temporary crises of all types in addition to those specifically related to water (Hussein and Nelson, 1997). Reliance on kinship or caste networks is a form of risk spreading or buffering. It gives households access to a larger pool of resources than they are able to accumulate on their own. Drawing down stockpiles of food or cash reserves and borrowing are also mitigation strategies, where coping focuses on reducing variability in livelihoods through buffering. Planned migration (regular patterns of seasonal migration) is a form of coping by adjusting livelihood strategies in ways that reflect anticipated variations in water availability. Development of permanent non-agricultural income sources is a form of averting behaviour.

The viability of many of the above household-level averting, mitigation and adjustment strategies varies considerably between locations and the target population. As Chen (1991) documents, women are often at a disadvantage with respect to many strategies. For example, in traditional Indian communities, women are in a weak negotiating position with respect to share-cropping arrangements, and they may be less able to migrate or seek employment outside the home. Furthermore, the ability to diversify income strategies depends on wider factors such as the demand for agricultural and other labour and the overall economic structure of a region.

In many cases, household-level coping responses, such as migration, occur in response to a mix of pull-and-push factors (better wages or specific opportunities in different areas and connections with individuals or communities, along with scarcity or limited opportunities in the home area). As with other strategies, migration entails costs as well as benefits. Much depends on how it occurs. Migrants often move into low-pay occupations, live in areas with few health or other services, and leave women, children and other dependants with little support in home areas. The social costs can be huge. At the same time, migration of one family member or the household as a whole can provide access to income, livelihood and educational opportunities for entire households that are not available in rural areas.

6.2.2 Institutional responses

In addition to household-level coping strategies, communities often develop institutions for coping with variability and scarcity. Two of the most common community-level strategies are the development of access-right systems and water markets. Access-right systems range from basic religious principles mandating access to available supplies for basic needs – such as the right of thirst in the *shariah* and similar sentiments in Christian, Jewish and other aspects of Islamic philosophy –, to grudging rights of survival (Wescoat, 1995; Brooks, 2001; Faruqui, 2001; Meinzen-Dick and Pradhan, 2002). Such rights systems essentially reallocate available supplies away from the uses that any individual may believe is best in order to meet basic survival needs that are agreed as fundamental at a community level. Communities also often impose other forms of access restrictions on water in times of shortage. For example, ponds are often reserved for livestock, and specific wells may be designated as only for high-priority domestic uses.

As seen earlier, water markets represent another form of institution for allocating available supplies. While markets based on legally-recognized and quantified systems of water rights are globally rare (the best documented being in western USA), informal markets operating at community level are common in developing countries such as India. While the impact of these is widely debated, they are widespread and play a major role in water allocation in periods of seasonal scarcity (Shah, 1993; Janakarajan, 1994; Moench, 1995; Janakarajan, 1999; Dubash, 2000). As water markets have evolved into a common institution for allocating available supplies during medium-term and long-term (fundamental systemic change) periods of water scarcity, their role as a coping strategy has been separately discussed in Section 4.5.

Above the household and community levels, governments are often involved directly in a variety of activities to mitigate the impact of short-term variations in water supply. Such strategies often include:

- crop and drought insurance programmes to mitigate the impact of scarcity on individuals and spread the risk of fluctuations over society as a whole;

- food-for-work or employment-guarantee schemes to mitigate the impact of short-term droughts or seasonal shortages by stabilizing incomes;
- buffering the impact of shortages through stockpiling food and distributing it at subsidized prices through public systems; and
- investments in meteorological forecasting and communication capabilities to warn populations of anticipated scarcity conditions and enable them to adjust activities on their own. For example, improved weather forecasting.

7. Institutional Implications

7.1 Capacity to engage at aquifer scales

Existing approaches to water management are not sufficient to address the particular nature of groundwater and the habits of use that have resulted in depletion and degradation. The capacity to develop, or permit the growth of, more pluralistic institutions representing users at appropriate aquifer scales appears to be a pre-requisite for managing groundwater. Dealing with this at local level is a priority. A clear understanding of the aquifer systems and their systems at their framework of respective levels of development risk and their inherent vulnerability, combined with smart support or policy space for organizations to occur is necessary. For all local initiatives, it is essential to determine who is really implicated in applying principles of 'good' groundwater governance. The overall institutional environment, including national legal frameworks for water management, may or may not be sufficient, but the local institutional arrangements tend to determine outcomes. Before adjusting the former (institutional environment), has enough been understood about the capacity of the latter (institutional arrangements)? Figure 2 attempts to illustrate why the relative scales of organization with respect to aquifers and hydrogeological evolution are important. Large consolidated aquifer systems will present challenges in regional integration while the 'atomized' development of thin discontinuous crystalline basement (hard rock) require a set of highly localised skills and capacities. Furthermore, the need to engage over a differential time-span in dealing with groundwater problems is also crucial in this regard. Shorter recharge programmes may significantly address groundwater exploitation in hard rock, strip alluvial and even karst systems, with impacts evident over a short period of time; on the other hand, longer, more engaging recharge programmes will need to be designed for restoring aquifer storages in deep alluvial and some consolidated sedimentary aquifers. Governance mechanisms, therefore, need to give importance to the typology-scale factor at the time of their designing phase.

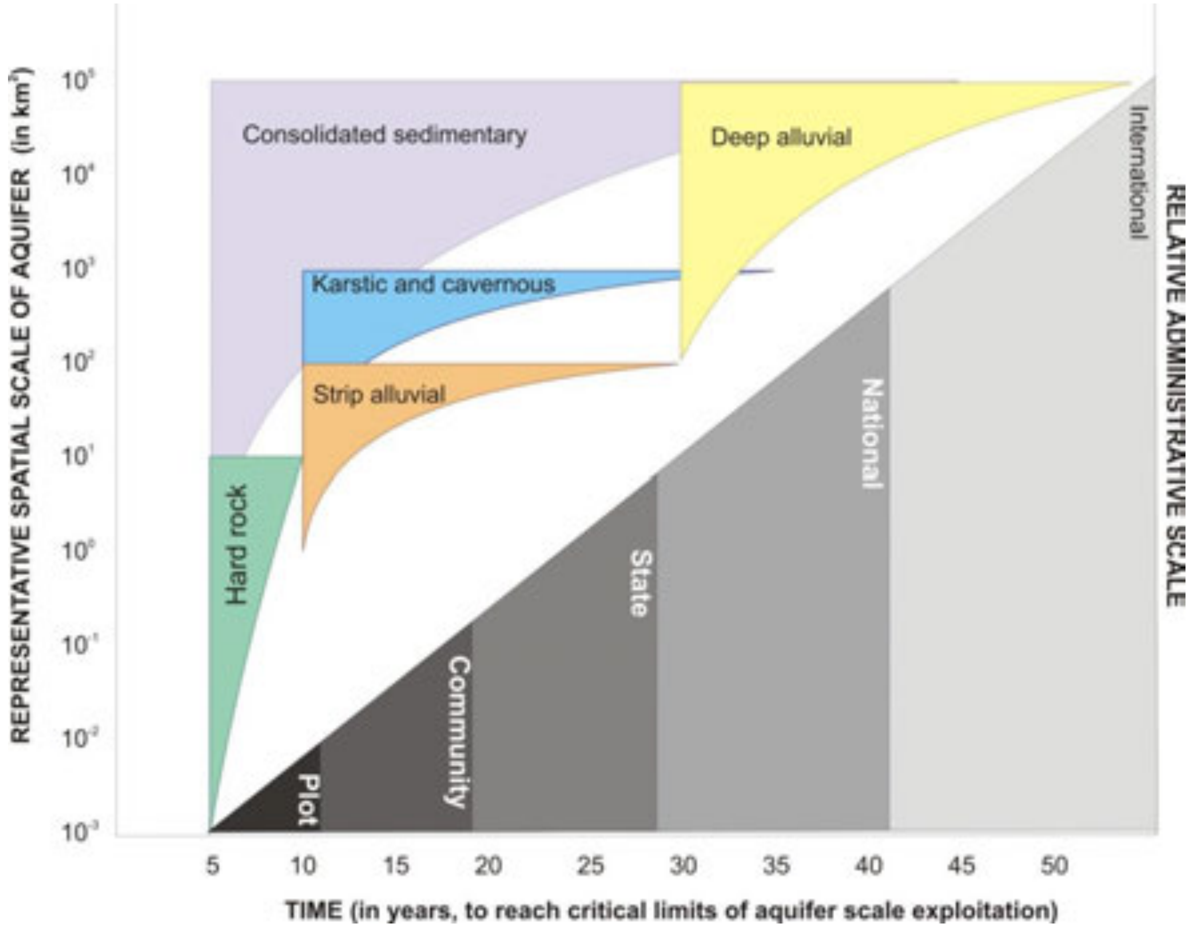


Figure 2: Conceptual diagram explaining aquifer typologies within a framework of spatial, temporal and response scales

A pluralistic institutional environment– composed of five enabling elements as identified below – plays a central role in creating the conditions necessary to address groundwater problems in an integrated manner. This implies that support – whether from external or internal sources – needs to be directed in ways that encourage the growth of such environments. If solutions to groundwater problems depend on a mix of technical/institutional capacity and the pressures/avenues for action generated by pluralistic institutional environments, then external support can play a critical role by catalysing awareness of problems and potential solutions and by supporting the development of appropriate capacities. The ability to develop such support and target it in ways that actually meet the needs in different contexts depends, in turn, on the recognition of both basic principles and commonalities between contexts – i.e. situations in which similar issues are likely to arise, where similar patterns of vulnerability/risk are likely to exist, and where similar response strategies are likely to prove effective.

Where groundwater issues are currently being addressed primarily by government departments– as they are in many locations – then support for the development of civil society and private-sector organizations working on groundwater may be particularly important. This is not to say that such organizations should be encouraged to duplicate regulatory or similar roles where governments are already very active. Private-sector organizations are particularly effective for the delivery of goods and services where such activities have strong market logic. They are less effective in providing public goods, particularly to groups with a limited capacity to pay. Civil society organizations tend to be effective when they represent the interests of specific groups (environmental, cultural, etc.). They can also be effective when they deliver public services to marginal groups, i.e. those who are not well served by the market. Where such organizations are weak, their strengthening represents a key strategy for increasing integration and the social capacity to address groundwater problems as they emerge.

The institutional environment is imbalanced wherever large groups are affected by groundwater problems, but have no organized voice in society and no organizations dedicated to meeting their basic needs. The environment is also imbalanced wherever strong market logic exists for private-sector activity in the delivery of goods and services, but the private sector is weak or its role is undermined. Finally, the context is imbalanced where the market or civil society organizations dominate and face no checks or balances through the regulatory and standard-setting roles of representative government. Recognizing the mix needed and, where there is a lack of balance, providing forms of support that encourage such a mix to evolve represents a basic starting point.

Five key elements form an essential capacity foundation for pluralistic groundwater institutions to grow and play effective roles:

1) *Freedom of information.* Where scientific and other information on groundwater conditions and the impacts of emerging problems or potential solutions are not part of the public domain, then the factual basis for effective contestation is undermined. Groups (whether in the government, civil society or the market) cannot be challenged, problems cannot be documented, and there is little factual basis for developing new management responses. Freedom of information is a basic enabling condition.
2) *A right to organize that includes access to appropriate financial mechanisms.* The right to organize is central to the role of civil society and community-based organizations. Unless the right to organize – whether for advocacy, service delivery or basic resource management purposes – exists, civil society cannot play any effective role. It is important to recognize that this applies as much to local community-based organizations for groundwater management as it might apply to a national environmental advocacy organization. Again, despite the fact that many regions exercise such a right, it often does not fall in the formal domain of rights in resources such as groundwater. Furthermore, the right must include the ability to access appropriate financial mechanisms. Where organizations lack the ability to raise funds, they generally lack sustainability and the ability to build capacity. Service delivery organizations require the ability to charge realistic service fees. Resource management organizations require the ability to assess fees or tax those using or depending on the resource. Advocacy organizations require the ability to accept donations or charge their membership. Financial mechanisms are a core element for translating theoretical rights of organization into reality.
3) *Enabling legal, regulatory and financial systems.* Legal, regulatory and financial systems that enable different types of organizations to form, and play effective roles in water management, are central to the evolution of pluralistic institutional contexts. In many situations, existing legal frameworks prescribe very specific organizational forms for activities such as groundwater management. They also allocate key financial mechanisms, such as the ability to charge fees or adopt local taxes, only to agencies within the governmental structure. Community-based organizations generally have no legal right to

designate areas for management, raise funds from those benefiting from management, or take any action that either restricts or enables any form of use. As a result, it is impossible for them to develop the capacity to play an effective management role. Key elements in legal systems that contribute to enabling environments include:

4) *Water rights systems that balance public and private interests.* The linkage between groundwater rights systems and the power to effect management in society has not been adequately explored. Rights systems that balance public and private interests – i.e. provide standing for both public and private perspectives on how groundwater should be allocated and used – would enable the types of institutional pluralism that this study contends are central to effective integration. Concepts such as private-use rights within a broad ownership of water held in public trust by the local governance body or the State may represent an avenue for this. Allocation of access –*via* linking the right to drill a well to landownership, drilling regulations and well licenses – is often practical. On the other hand, the introduction of volumetric allocation systems has proved difficult to implement for a variety of social and technical reasons. This is why debates over groundwater rights systems, a central feature of management debates in the 1990s, have made little practical progress. However, it is important to emphasize the inherent limitations and lack of balance in attempts to develop rights systems.
5) *Systems for dispute resolution.* If integration is an outcome based on contestation discussions within pluralistic institutional environments, then systems for dispute resolution are essential. In parts of the USA, specialized water courts play this role. Where groundwater is concerned, dispute resolution is often rendered difficult because of the uncertainty in the behaviour of the resource itself. Therefore, unless the previous four key elements are strengthened and addressed, systems for dispute resolution may not evolve effectively.

These five elements (freedom of information, the right to organize, enabling legal, regulatory and financial frameworks, balanced equitable water rights systems and dispute resolutions systems) represent the basic foundation for institutional pluralism in water. It is this pluralism that gives society the flexibility and capacity necessary for integration and continuous generation of 'solutions' as groundwater problems or other constraints emerge. This is a critical area where regions need to learn from one another. Globally, most efforts to share insights on topics such as groundwater have focused on specific technologies and specific management models. These are often posed as "best practice" examples. However, the focus needs to shift towards basic principles, and to the diverse ways these can be achieved in different contexts and at different phases of development.

Effective responses to any groundwater issue are unlikely to rest on any single set of solutions (such as the development of specific management or allocation systems). Instead, multiple answers that respond to multiple contexts are required. These are most likely to emerge from the ferment present in pluralistic institutional environments. However, there are commonalities between contexts, and these commonalities can assist in developing courses of action that are much more targeted (and perhaps more satisfying) than the broad principles or key elements presented above.

7.2 Agreeing common goals

The flow of groundwater through aquifers may be complex, but actual management practices can be as simple as agreeing maximum acceptable drawdowns in pumped wells or banning the storage and application of pesticides across an aquifer that furnishes potable water supplies. These can be things that a well-identified community of groundwater users can agree upon, if basic information is made available and explained (Thematic Paper 7). How groundwater managers engage with user communities at the outset is important. If water resource agencies have failed to 'socialize' groundwater because of technical preferences for hydraulic management, then a quiet revolution within the agency might be required to establish a legitimate and respected platform to engage groundwater users. Equally, an initiative could be promoted as an autonomous self-governing adaptation, in which case the water agency may simply have to avoid interference.

Therefore defining mutually acceptable levels of depletion and degradation on the basis of clear information and a fundamental understanding of groundwater circulation through aquifer systems is likely to be a firm starting point.

7.3 Spreading risks: an economic and livelihoods issue

Attempts to insure against fluctuations in precipitation and water availability may be as old as livelihoods based on agriculture. Buffering strategies – the accumulation of food, animals or other forms of capital as a reserve for use in scarcity periods – are common at household, community and national levels.

Some of the specific strategies used to buffer income and spread risk at household level include:

- maintenance of household or community grain reserves between seasons and years;
- investments in assets, such as gold, jewellery or animals that maintain value and can be exchanged to meet subsistence or other needs in times of scarcity;
- diversification of crops between income types (subsistence, cash and, within cash, between market types), seasons, and vulnerability to disruption[2];
- development of patron–client and kinship relations that provide vulnerable members with some assurance of access to essential resources in times of scarcity;
- sharecropping, where risk is spread between cultivator and landowner; and
- income diversification.

These initiatives may be supported at State or national level with:

- formal crop insurance programmes (state or private-sector financed);
- food buffer stock programmes (India is a prime example) that generally involve large purchases of grain during good years accompanied by releases during drought;
- subsidized public distribution systems;
- food-for-work and similar publicly financed drought-relief or employment-guarantee programmes targeted at vulnerable populations (Rao *et al.,* 1988)[3];
- governmental policies designed to ensure food security by subsidizing production within the country;
- governmental purchase of food from international markets with internally subsidized distribution; and
- financial hedging instruments – products offered by commercial banks to farming cooperatives to provide producers with floors on commodity prices (e.g. coffee put options for Ugandan coffee producers).

Even international level support can be significant as with:

- humanitarian assistance programmes through bilateral or multilateral agencies;
- proposed international food buffer mechanisms; and
- international systems for grain trade (markets).

All forms of buffering and risk spreading have costs of their own. India's food buffer stock programme has recently been widely criticized as wasteful with amounts of grain that are lost to pests or decay by being stored in poor conditions. As a result there is an increasing belief that shortages can be addressed through global food markets.

7.4 The interaction between forms of coping and the nature of water supply disruptions

In many cases, approaches to coping with short- or medium-term droughts are integral parts of household and community livelihood strategies. They are embedded in existing social institutions, such as kinship networks, informal water markets and patron-client relations. Increasingly, as discussed below, such household-level coping strategies are interlinked with wider changes in society. However, as Chen (1991) notes: "unlike private drought management by individual households, public drought management has been developed in isolation from on going development strategies or chronic subsistence needs." In most cases, public drought-

[2]In Kerala, India, home garden systems often contain more than 40 types of crops (from vegetables to trees) with widely different maturities and income characteristics (Moench, 1991).

[3]Chen (1991, citing Rao, Ray and Subbarao, 1988) indicates that such "employment programmes, notably the Employment Guarantee Scheme in Maharashtra, perform an important role in stabilizing incomes and employment across seasons."

management responses and humanitarian assistance have attempted to mitigate the immediate impact of drought, but they have done little to alleviate the core problem by addressing more fundamental, systemic development needs.

This is a major limitation in the food-for-work and water harvesting programmes commonly implemented in arid areas of India during droughts. In many situations, these programmes employ thousands of people to “move dirt” and construct small dams. However, evidence suggests that in many cases such water harvesting programmes have a limited impact on water availability and do not address long-term groundwater overdraft problems (Kumar *et al.*, 2006). While they provide employment and place food or money into the hands of drought-affected populations, the populations are encouraged to remain in place and not supported in moving away from vulnerable livelihoods.

Coping strategies range from household-level techniques to “make it through” bad times by reducing consumption up to fundamental changes in livelihood systems. As Box 4 illustrates, in many situations, multiple strategies are used in conjunction or sequentially as water scarcity increases. Furthermore, changes in regional economies induced by coping with temporary water scarcity (i.e. drought) can cascade into long-term changes in economic and social structures.

Box 4: Coping with drought in Zimbabwe

Drought is part of the normal pattern of life in Zimbabwe. However, in 1991–92, the whole of southern Africa suffered a major drought, a complete failure of crops, and the exhaustion of national food reserves. The situation was monitored, and a pattern of sequential responses was seen.

First, minor adjustments such as diet changes or increased reliance on off-farm income sources took place, followed by the disposal of assets, notably poultry and goats, and major shifts in practice such as outmigration. Understanding this pattern is vital if external support is to complement local coping strategies. Non-farm income-generating activities are critical to people’s survival both during drought and non-drought periods.

With the reduction in real wages and retrenchments caused by structural adjustments, the value of remittance incomes has decreased dramatically in the last few years. During the drought, an expansion in trading activities and the sudden explosion of gold panning were seen. It also prompted widespread diversification of non-farm livelihood activities, among men and women, as well as a shift in investment in agriculture.

Following the death of many cattle, and given the inability of people to afford to purchase new animals, there was a severe scarcity of draught power. Farmers were unable to purchase inorganic fertilizers, except in very small quantities. The result was a shift towards more intensive investment in small gardens and home field plots, using the limited draught power for cultivation and any available organic materials for fertilization. This resulted in the growing of premium crops on prime arable sites, such as low-lying wetlands, where crop yields are more certain.

Source: Mombeshora *et al.* (1995).

As outlined in Table 2, different coping strategies apply to different types of problems. Risk-spreading strategies (whether formal insurance or techniques such as share-cropping) are useful in response to variability and uncertainty, but generally cannot be applied to situations where changes are either certain or are expected to be long term. Risk spreading is applicable to stochastic processes, where probabilities and consequences can be estimated but the timing or location of impacts is not well known. They are not directly applicable to situations of near certainty – such as depletion caused by sustained groundwater abstraction. In this latter case, other strategies such as migration, fundamental changes in livelihoods, intensification, and reallocation of available supplies are more applicable coping responses.

Table 2: Matrix of coping mechanisms

Predictability of scarcity	Duration of scarcity Short (within years and seasons)	Medium (multiyear)	Long (fundamental system changes)
Certainty	Shortages of a few hours to a few weeks during, for example, planned irrigation or power-cut rotations. Schedule activities to reduce water dependence at times when supply is disrupted. It is necessary to study the disruption patterns in order to cope efficiently; seasonal cropping systems are one example. Seasonality: changes in water availability between seasons within established and stable climate systems. Build in system redundancy and storage	Supply deficits while new supplies are being developed or imported. Example: overdraft in Arizona while waiting for central Arizona project construction. Overdraft in Ahmedabad, Gujarat, while waiting for water imports from the Narmada Project. Unsustainable use of alternative sources while new sources come on line.	Long-term water availability declines where fossil sources are being used or mining is occurring. Ogallala Aquifer depletion is a prime example. Planned changes in water-use systems and water dependency; and gradual, unplanned, adjustments in economies and livelihood strategies as individuals and communities respond to anticipated changes in circumstances.
Stochastic	Variability in precipitation within seasons. Common gaps in water availability of a few days to a few months. Wells to supplement supply and local storage ponds are typical coping strategies. Rapid fluctuations in groundwater levels in low-storage aquifers. Risk spreading – insurance strategies. Predictability is variable. Evolution of institutions for flexibly reallocating water.	Significant variations in precipitation availability between years including the cyclical patterns evident in existing hydrometeorological datasets (years to a few decades). Diversification and risk spreading. Long-term fluctuations in groundwater availability related to cyclical changes in precipitation and pumping levels (overdraft in dry years, recharge in wet). Evolution of institutions for flexibly reallocating water.	Permanent (from a human perspective) changes in groundwater availability related to mining of fossil water or long-term climate fluctuations. Avert: change livelihood systems.
Unpredictable	Short-term problems that affect water availability through established supply systems (infrastructure failures caused by, for example, earthquakes, design or maintenance flaws, terrorist actions). The timing of many of these is highly unpredictable. Extreme events (short-term droughts not experienced in historical record). Risk spreading – insurance strategies and evolution of institutions for flexibly reallocating water.	Changes in water availability owing to major political or economic changes (impact of war on economies, etc.). Diversification and risk spreading. Extreme events (medium-term droughts not previously experienced in historical record). Evolution of institutions for flexibly reallocating water.	Changes in water chemistry or water availability owing to lack of basic scientific knowledge concerning the impact of groundwater development (arsenic or selenium contamination, compaction). Changes owing to introduction of new technologies (spread of pumps). Highly adaptive systems capable of making fundamental livelihood changes.

As noted above, the most challenging situation occurs when long- and short-term processes reducing water availability coincide. Drought in conjunction with groundwater overdraft represents a much more fundamental challenge than either process occurring on its own. However, this is a situation where short- and long-term coping strategies could be used in conjunction to enable fundamental changes in resource use and move populations towards more sustainable livelihoods.

Part 3 Prospects

8. Institutional Targets – When and Where to Innovate

It is now possible to bring together three governance dimensions: (1) the fundamental features in the groundwater environment (aquifer typologies); (2) the broad patterns of change that occur as development proceeds (development phases); and (3) the combination of direct management, indirect influence and adaptive response strategies available on the 'palette'. This convergence is required in order to identify the potential courses of action that those concerned with groundwater could implement in different contexts. Three broad arenas of action exist: (i) direct water-focused management actions; (ii) indirect interventions designed to influence the way water is used within current applications; and (iii) adaptation – interventions intended to support changes in the underlying social structures that determine groundwater dependence and use. The suggestion here is not that the courses of action put on the palette are a final prescription to all groundwater problems, even within a single typology. Instead the palette provides broad guidance on potential responses at different stages of development within typologies. The types of strategies that may prove effective also vary over time (both the phase of groundwater development and the presence or absence of specific windows of opportunity) and the hydrogeological setting (represented here by the aquifer typology).

In order to identify practical courses of action, those concerned with groundwater management need to bring together considerations related to regional hydrogeology, the phase of groundwater development and the socioeconomic context in order to develop a palette of direct, indirect and adaptive intervention strategies that respond to both groundwater opportunities and emerging problems. The goal is not to build a single "integrated" approach but instead to identify incremental courses of action – appropriate at given points of time, in given local hydrogeological contexts – that respond to social needs and to the constraints, issues and opportunities that groundwater conditions present. The goal is to develop approaches that enable actors to identify, and act on, incremental elements – pieces within an ever-shifting mosaic – that improve the wider relationship between groundwater and society

As seen earlier, the response space for managing groundwater involves three dimensions: the nature of the aquifer and groundwater resource base, the stage of development and the socioeconomic/institutional context. Because of its relatively static nature, the hydrogeological context is particularly useful for organizing presentation and discussion of issues. The institutional environment is, however, of critical importance in shaping the array of management avenues that are possible, at a practical level, to address needs emerging at different stages of development and in different hydrological contexts. As a result, 'unpacking' the response space to identify viable avenues for management is an essential first step.

The institutional contexts for local groundwater management range across a spectrum, from ones that are highly organized and structured to others where institutions are weak and actions are dominated by highly individualistic behaviour. Three primary factors can be identified:

1) strength, scale and penetration of hierarchical governmental and quasi-governmental institutions;
2) extent and strength of group, identity or place-bounded institutions (the "village," "tribe" or "community"); and
3) penetration and organization of market networks and the actors (individuals and businesses) within them.

Management possibilities vary greatly depending on the relative balance between these different institutional forms. In areas where governmental, market and community-based institutions are weak (as in many post-conflict zones) most behaviour is highly individualistic. As a result, from a social and institutional perspective, the capacity to proactively "manage" groundwater (or most other) resources is extremely limited, and responses need to focus on enabling individuals to adapt. In highly institutionalized environments, in contrast, more direct and proactive adaptive management approaches may be much more viable. It is important to recognize, however, that the strength of different institutional forms is highly variable in different contexts – strong hierarchical institutions, for example, often exist where markets and community-based institutions are weak and *vice versa*. Since the nature of existing social institutions plays a major role in determining how societies can respond to emerging needs, unpacking this a bit further can provide critical insights into the array of management strategies that are likely to be viable in different institutional contexts.

9. Prospects for Aquifer-Scale User Institutions

9.1 Regulation and hierarchy

Where hierarchical governmental and other institutions are strong and penetrate to local levels, the ability to both regulate behaviour and undertake other direct forms of management activities tends to be strong as well. Governmental institutions may, for example, have the mandate and resources to build and maintain physical structures such as dams, recharge facilities and water transport (irrigation or water supply) systems. Some may regulate a wide variety of factors such as land-use patterns, well depths and spacing or water uses that have a major direct impact on groundwater conditions. There are cases where such strong regulation matters.

However, in the absence of outside pressure from individuals, communities or market institutions, hierarchically organized institutions tend to be driven by "perspectives from the top." They are generally formed around a cadre of professionals who have been trained within the bounds of a specific set of perspectives and tools. They frequently have difficulty in responding to location-specific or rapidly changing and evolving conditions. In addition, they often have difficulty incorporating or responding to sources of information and/or perspectives that fall outside conventional professional spheres of action. "Water resource" departments, for example, tend to emphasize physical management interventions (the building of structures) or regulatory approaches where they have direct control over outcomes, rather than indirect management measures or interventions that would assist local populations to adapt.

In many cases, the ability of hierarchically-organized institutions to actually intervene in ways that affect conditions at the ground level is limited by their degree of penetration. In practice, for example, government organizations may have limited capacity to actually influence the behaviour of individuals or face resistance from community-based and market or other networked institutions. Similarly, while hierarchically-organized institutions can generally build physical structures, for a variety of budgetary and other reasons, their ability (or interest in) operating and maintaining such structures can be limited. As a result, on a practical level, the ability of hierarchically-organized institutions to manage conditions on the ground is often limited.

9.2 Consolidation of community institutions

In contrast to hierarchically-structured governmental organizations, community and other place-based organizations are often able to draw upon a wide array of location- and context-specific information. Over the past three decades, research and practice have demonstrated that a number of conditions are required for effective management of common property resources. If those conditions are met, communities and other group-bounded organizations can contribute to effective groundwater management at the local level. Where communities and other group-based organizations are strong, for example, they can often intervene in ways that directly contribute to management. Such interventions can range from the construction and operation of water management structures to regulations on access to and use of available water supplies.

The conditions under which common-pool resource management approaches are likely to be effective, however, are relatively restrictive. They include:

1) clear boundaries on the resource being managed;
2) transparent information on resource dynamics, use and condition;
3) relatively small group size, homogeneity and clarity on the boundaries of the group; and
4) ability to exclude or control free-riders (those who benefit from but do not contribute to management).

In many cases, the ability of communities or other group-bounded organizations to contribute directly to the management of groundwater resources is limited by: (i) the lack of technical expertise (which undermines the ability to understand resource dynamics, use and condition); (ii) the aquifer scale (which increases group size and heterogeneity); and (iii) institutional feature (such as the legal linkage between rights to access groundwater and land ownership in India) that limit the ability to exclude free riders. In addition, communities and other group-bounded organizations are often in conflict with governmental and other hierarchically-organized institutions.

Finally, community organizations are often undermined by the rapid evolution of markets and other networks. This shifts both identity and practical dependency away from the local or regional level at which aquifers operate.

Beyond direct management of groundwater, community and other group-based institutions often either enable or constrain management environments, through the role they can play as counterpoints to both hierarchical and networked institutions. Group-based institutions are often politically very active. In some cases, this blocks the ability of hierarchical organizations to regulate water use or take other action within their mandate. On the other hand, pressures may also push hierarchical institutions to move beyond their normal professional or operational "comfort" zone to address certain concerns or take courses of action they would not have taken on their own. Similarly, they can link with markets or social networks in ways that change both use and patterns of dependency on groundwater resources. In Yemen, for example, community organizations financed by remittances from social networks of expatriate migrants are directly involved in regulating groundwater resources. In other cases, environmental organizations are the primary politically active advocates forcing government organizations to regulate water quality and control pollution from market actors.

Overall, the role community and other group-based organizations can play in management depends on the nature of the organization (whether, for example, the group is defined by a shared location or some other form of identity) and their relationship with other institutional forms. Where institutional dynamics create deadlock, this limits the possibilities for direct management of groundwater resources and necessitates greater emphasis on adapting to emerging conditions. Where institutional dynamics operate in synergy, possibilities for proactive management are greater. It is important to recognize that institutional conflicts can evolve in ways that contribute to management as well as deadlock. Political action by group-bounded organizations can, for example, be the essential input required for government organizations to initiate regulatory action. In other cases, however, similar forms of political action by communities or interest groups can block effective action. Understanding these dynamics is, therefore, central to recognizing the role institutions can play.

9.3 Economic incentives to cooperate

Markets generally play a minor to non-existent role in direct groundwater management, but they often play a central role as the primary mechanism for groundwater development (by delivering pumping equipment and well-development services and creating the demand for products with significant groundwater input). Markets are also often directly involved in groundwater service delivery – the tanker-based drinking water markets found in most cities across South Asia and parts of the Middle East-North Africa region being a case in point. Finally, individualistic behaviour of businesses and households (as well as individuals) in markets is the primary mechanism through which adaptation occurs. Individuals, households and businesses (the "agents" acting within markets) respond to the opportunities and constraints they perceive, in any given situation.

During the early phases of groundwater development, the primary challenge has often been to make such agents aware of the benefits of groundwater and to develop the market-based supply and demand chains, which are necessary to provide development services and to link producers with demand centres. This was the case, for example, in India during the 1960s and 1970s and may be the case in large parts of Africa at present. Once market mechanisms have ignited demand for groundwater as an input to production, this becomes a driving factor underlying increasing levels of development. The attendant overdraft and quality issues emerge in later phases. As groundwater scarcity and major quality issues emerge, market mechanisms drive much of the search by agents for alternatives. Where livelihoods are concerned, this provides the pressure for shifting away from intensive groundwater-dependent forms of economic activity, such as irrigated agriculture. It can also create openings for new products – such as bottled-water markets that are common in many parts of the world – as high-end consumers try to avoid health issues associated with low-quality drinking water supplies or seek convenience and other benefits.

Unlike hierarchical government or community-based organizations, markets as institutions do not exist within a framework that defines specific goals, nor do they exercise agency to meet such goals. They cannot be "created" with the purpose of groundwater management and they do not work toward that (or toward adaptation) as an "objective." Instead, markets are largely self-organizing emergent phenomena where agency is exercised by individuals, households and businesses to meet their individual needs in response to the opportunities and constraints they perceive.

Using market mechanisms as part of an overall strategy to respond to groundwater-related issues, during different stages of development, depends on interventions by governments, community-based or other organizations to provide incentives and regulate the functioning of markets and the relations between agents operating within them. Numerous mechanisms for this exist, including:

a) *Provision of information.* Information on resources (whether related to availability, scarcity or quality), technologies and users will shape the behaviour of market actors.

b) *Support for technological innovation.* Historically, substantial governmental investment was directed into the development of pumping technologies and, more recently, into technologies for efficient water use. Improved crop varieties have also been a major focus of investment. Numerous similar opportunities exist that would help regions to adapt to scarcity or quality issues.

c) *Finance and financial mechanisms.* Extension of credit or in some cases subsidies for individuals, households and businesses is often critical in early stages for developing wells and irrigated agriculture; and in later stages for diversifying into other livelihood or business activities.

d) *Extension services*. This could range from technical advice to support for the development of supply chains and market creation.

e) *Investments in the underpinning systems that enable diversification.* Basic systems are the foundations that enable people to shift livelihoods as conditions change. They are essential at early stages of groundwater development to enable the growth of agricultural markets and at later stages of groundwater development to enable the growth of non-farm livelihoods.

f) *Regulation.* This can involve direct regulation of groundwater (source protection, pollution control, etc.), regulating the factors that enable groundwater access (drilling rigs), and regulation of activities (such as bans on water intensive forms of agricultural and industrial pollution) that can shape the demand for groundwater. Depending on the aquifer typology and the governance environment different mixes of regulatory measures may or may not be possible at different phases of development.

Overall, as the above listing illustrates, numerous mechanisms exist to shape the behaviour. While these would often be implemented by government organizations, in many cases community-based or other organizations can and do play a significant role.

10. Conclusions

Trends in local groundwater management institutions cannot be assessed systematically due to the scattered nature of available information. Instead, stocktaking has to rely on anecdotal evidence pulled together from disparate sources and geographies. This disparity exists at different scales – regarding aquifer systems within a contiguous region or across countries. Overall, however, it is clear that local or aquifer-based groundwater user management has been an area of policy neglect. A general conclusion from the baseline literature and this diagnostic is that autonomous self-regulation is unlikely to have any impact, unless the institutional environment is conducive and the rights and obligations with respect to groundwater and groundwater protection are accepted. Furthermore, available experience suggests that even if local policy and resource management issues are addressed, local arrangements will, for a variety of social, economic, institutional and political reasons, be insufficient to address the governance 'gap' required to conserve resources and prolong groundwater-dependant livelihoods. To put it more bluntly, conventional approaches to groundwater management appear insufficient to address emerging depletion, pollution and other groundwater problems.

The analysis in this Thematic Paper suggests that the inadequacy of conventional groundwater management approaches reflects the complex array of social, economic, institutional and political as well as technical factors that determine interests, access and the ability for any group to exercise a degree of control over groundwater conditions. There are inherent limitations to any approach that seeks to protect human interests in groundwater, or any other major natural system, through approaches to management that are 'resource-focused'. Groundwater is, furthermore, a particularly complex resource where, unlike surface water, groundwater access is determined by a combination of overlying land use/ownership patterns and 'invisible' and difficult to assess hydrogeological structures and processes. As a result, access is spatially highly distributed with few of the clear social/institutional control points that are present in surface water networks. This creates often-fundamental challenges for the development of institutional rules and organizations that would be required to manage the resource directly. This challenge is intensified because most management approaches emerge from technical considerations related to the groundwater resource base and are also poorly linked to livelihood strategies and the incentives that local populations actually face in relation to groundwater use. For these reasons, the development of a wider policy perspective is essential to frame 'good groundwater governance'.

What does "development of a wider policy perspective" mean? Primarily it means that approaches to addressing actual or emerging groundwater problems need to focus beyond the resource base itself and engage effectively with the social and economic context that shapes incentives for groundwater use amongst communities of users. Achieving effective management outcomes, we believe, depends on the wider governance environment and the development and livelihood choices that environment generates. Broad recognition of, for example, regional water scarcity can serve as a basis for decisions on regional economic development that emphasize low water intensity livelihoods. This type of approach, which focuses on to the wider overall environment governing development pathways, represents an arena of potential opportunity for addressing groundwater problems that is quite distinct from and relatively less explored than more narrowly focused technical groundwater management strategies. Furthermore, governance frameworks that enable societies to make this type of choice could reduce dependence on groundwater while also potentially creating opportunities for more direct conventional management of the resource base. Clearly, this does not mean moving away from developing improved understanding of the resource; rather, it means improved understanding leading to a much wider thinking about responses to groundwater-related problems rather than a focus on the resource base itself. Groundwater-specific management goals may need to look beyond straightjacket regulatory mechanisms and look for alternative niches in livelihoods, energy use and opportunities offered under adaptation and coping strategies that focus on events such as droughts, floods, economic drivers and even climate change and variability. For this to happen, public and private institutions will have to learn to work effectively with groundwater users and groundwater management organizations. The formation of 'institutional homes' for groundwater at all levels should merit more attention in the future.

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Social Adoption of Groundwater Pumping Technology and the Development of Groundwater Cultures: Governance at the Point of Abstraction

Digest

Relevance

Paper 8 traces the development of the earliest forms of groundwater governance centred on the ownership and rights to water that were adequate for the then, low-capacity of hand-, wind- and water-powered lifting devices. These principles were embodied in the rule-of-capture common law. From middle of the 19th century a pattern emerges where early in a development cycle the rapid and unrestrained take-up of new pumping technology leads to the overexploitation of groundwater resources that prompts retroactive legislation. Since 1900, progressive developments in rotodynamic pumping technology and motive power have underpinned an ever-expanding worldwide use of groundwater. These enable the exploitation of deeper aquifers, subsequent a step increase in competitive resource depletion and renewed cycles of retroactive legislation.

The paper examines the range manual and motorised pumps available and the industry's and regulators' approaches to improving their reliability and efficiency. The economic trend in assessing groundwater lifting based on the life cycle concept is reviewed. It evaluates the impact of the various subsidies available to irrigation farmers. It also examines the past and future self supply developments based on hand pumps for rural water supplies and the drive for the decentralised management of small-town piped water supplies that highlight the need for adequate supporting legislation.

Coverage

Four methods to lift water vertically against gravity from dug-wells or boreholes are reviewed:

- direct lifting of a fixed volume with a container – rope and bucket(s);
- positive displacement of a volume by the movement of a plunger or intermeshing rotating walls;
- rotodynamic propelling water by rotating blades or impellers;
- differential pressure by lowering the density of a water column – airlift.

Paper 8 concentrates on the three major groundwater uses, namely for rural and urban water supplies and for irrigation. Un-motorised rural water supplies are largely met by direct lifting or positive displacement devices. The viability of the VLOM (village level operation and maintenance) hand pumps is evaluated and found to be heavily reliant on the installation quality and subsequently on the available O&M (Operation and maintenance) expertise and a robust supply chain. Two main tiers of urban water supply are recognised: the large metropolitan water companies have access to the latest developments and efficient pumping technologies whereas the locally managed small-town piped water systems require coherent legislation to function effectively and sustainably.

The rapid development of robust diesel and electric powered rotodynamic pumps when coupled with the introduction of the centre pivot in the 1950s kicked-off an exponential growth in groundwater irrigation. To a large part, submersible pumps coupled with rural electrification considerably added to the productivity of India's 1970s Green Revolution. In many countries the adverse impact of expanded use of submersible pumps on groundwater levels and/or quality is yet to be met by appropriate governance measures.

Issues and limitations

As the central focus of all groundwater issues, the point of abstraction must match the owners' expectations in terms of yield, quality, reliability, sustainability, effort and cost. From the regulators' side the main issues are ensuring the sustainability and protection of the quality of the groundwater resource. The limitations to abstraction revolve around the groundwater availability that is dominated by the nature of the groundwater occurrences and the aquifer recharge regimes. The limits to groundwater abstraction are further dictated by the available pumping technology and access to, and the cost of the energy sources.

The historic efforts behind the deep step-wells and Borana tula wells demonstrate how communities can collectively meet and manage their groundwater supplies. This demand-led, self sufficiency contrasts with the often need-based, water supply programs that were implemented in response to the 1981-1990 International Drinking-Water Supply and Supply Decade (IDWSSD). The rapid expansion in the large-scale groundwater use for urban water supplies and irrigation exposed the resource limitations and unsustainable depletion that required addressing by technically sound allocation of water rights tailored to either a balanced resource usage or a controlled depletion regime. Experience has shown the allocation system requires continuous monitoring and abstraction licenses periodically revised. A major external issue with groundwater irrigation is the role of commodity or energy subsidies that further drive aquifer depletion.

Key findings

Key topics addressed in Paper 8 are:

- Development of pump and energy source technology;
- Escalating and diversification of groundwater usage
- Regulation of the ownership and rights to abstract groundwater.

The two aspects of pumps reviewed in detail lie at the either end of modern technology. At the bottom end, the demand for robust, affordable and easily maintained pumps suitable for rural water supplies has been met by a variety of hand pumps that only partially fulfilled these criteria. Many reviews of rural water-supply programs point out how the benefits fail to reach the poorest in the target communities unless founded on strong community participation throughout the project formulation and execution. At the beginning of the 1981-1990 IDWSSD many donor projects moved into communities, constructing boreholes and wells equipped with hand-pumps with the minimum of consultation. In the worst cases no provision was made for maintenance of the pumps, nor was the ownership clearly defined. Often within a matter of a few months many pumps were broken down with failures often traceable to poor original design or installation. The alternative of substituting small, low-cost (>US $ 1 000) electric submersible pumps using wind or solar powered generators is increasingly viable and certainly should be considered in parallel with rural electrification programs with broken-down hand pumps being replaced with such submersible pumps.

At the high technology end, besides major groundwater urban supplies, irrigation farmers are the main users of high-capacity submersible and shaft turbine pumps. Here the focus is on the price of energy that makes up to 95% of the life cycle costs. Advances in variable speed drives will lead to high pumping efficiency.

From 1850 onwards, the impact of increasing abstraction on groundwater levels became increasingly obvious and the barriers to well-regulated groundwater abstraction rights that emerged include:

- insufficient monitoring and knowledge of the groundwater resource being developed;
- an entrenched pattern of prior uncontrolled groundwater abstraction;
- delayed recognition of or reluctance to address the adverse impacts of prior and on-going abstraction.

Inadequately-controlled groundwater use for irrigation can be addressed by either a hands-off approach where the uncontrolled development continues until abstraction becomes unviable due economics, soil salinization or water quality deterioration: or a second approach based on the orderly application of well-founded water right legislation supplemented with less formal tools for effective local management. These include:

- improving irrigation efficiency;
- defining well-spacing;
- imposing a moratorium in new borehole construction;
- restricting or banning the planting of high water demand crops, notably sugar cane;
- placing temporal limits to the groundwater irrigation cycle.

Alone, or in conjunction, these measures can moderate groundwater level decline. However, where they are farming community-based, they are frequently found to be fragile arrangements that breakdown with time as community priorities change or conflicting external developments provide alternative sources of irrigation water. Ultimately successful governance requires user acceptance and political backing.

Reappraising the culture of subsidies

Regional contrasts in the application of subsidies are instructive. Across Africa, much of the colonial water resource legislation was aimed at promoting economic growth. Annual development budgets included a variety of grants, rebates and subsidies for the borehole drilling for private individuals. From the late 1960s, the Asian green revolution has seen a much more extensive use of subsidies for groundwater irrigation to achieve food self-sufficiency and improve rural livelihoods. Some subsidises are directly tied to groundwater abstraction and some indirectly impact on the irrigation pattern. Direct subsidies cover the drilling of tube wells, provision of pumps and fixing energy costs. The indirect subsidies cover inputs – seeds and fertilizer – and outputs – largely guaranteed crop prices. They also can include tax breaks on capital investment and, more questionably, attempts to claim a groundwater depletion rebate as proposed in some States of the USA.

Initially justifiable, subsidies are frequently multilayered and indiscriminately applied to the extent they have become counterproductive from the point view of the user and resource. Essentially direct subsidies to groundwater irrigation largely undermine the legislators' ability to control the resource usage unless they are prepared to take the potentially politically damaging decisions to realign the system at a later date.

Future prospects and recommendations

The current groundwater-pump market ranges from rural water supply hand-pumps, through low-powered mechanized pumps for small-scale rural and urban water supplies, to powerful electric submersible pumps for urban, irrigation, industrial and dewatering purposes. All users expect their pumps to be efficient, durable and easy to service and to operate with minimal downtime. Among informed users, the purchase price is of much lesser consideration than meeting these requirements. At the bottom-end of the market, the hand-pump continues to prove problematical.

Small-town piped water supplies

Groundwater developments for small-town supplies serving populations between 2 000 and 100 000 are a focal point of many MDG (Millennium Development Goals) projects. Most schemes follow an established model employing consultants for design and supervision and qualified contractors for construction. While the schemes are mostly devised and negotiated by central or regional government, under decentralization, post-commissioning O&M is undertaken at the town or district level. A replacement hybrid donor-funded model is suggested where technical assistance teams design and supervise the construction of the more technically demanding system components (the borehole drilling contract, the electro-mechanical equipment, the transmission mains and storage tanks) and leave the simpler design and construction of the distribution system from the storage tanks to the local water points to local user groupings. The advantages of equipment standardization are widely recognized along with a supply chain where broken parts are exchanged for refurbished parts in order to reduce system downtime.

Several post-commissioning, small-town management models have been adopted for the operation and maintenance of public borehole supplies. Under full decentralization, community water boards are established to collect and manage revenue to cover future scheme operation, maintenance and expansion. The community water boards have the option to undertake this work directly or using private companies under contract. Other models include local government management through regional water supply agencies or more centralized government water supply operators responsible for all the small towns in the country. However, more effort needs to be directed to collection of long-term groundwater level data to determine if the abstraction exceeds the sustainable yield of the aquifer. All management models rely on sufficient trained staff and funds plus a robust supply chain. Pumping equipment suppliers should be encouraged to offer long-term leasing agreements covering maintenance and replacement of the pumps and control equipment. Non-payment of water charges by state and para-statal institutions is a common management problem to be addressed.

Improving irrigation livelihoods

At the bottom end of the irrigation market, the profusion of low-powered, motorized pumps available to the rural communities have a mixed record for durability and efficiency. However, before brand leaders emerge in terms of customer satisfaction, the low-income consumers can be protected by an international approval certification system. Another step available to improve small-scale groundwater irrigation efficiency is the use of mini-centre pivot systems by marginal and medium scale farmers. USA manufacturers are producing 27 to 30 m radius systems that cover around 0.25–0.4 ha. With a wide range of sprinkler application rates and up to 1.8 m clearance, using these to replace fixed sprinkler systems will provide significant water savings for cereal crops.

Improved pump technology

Major manufacturers continue to develop more efficient pumps and control systems. The main areas for improvement focus on optimizing pumping efficiency by balancing the discharge pressure and yield. With installed pumps usually over-specified in terms of both pumping head capacity and discharge, throttling back yield is often achieved by partially closing a valve to choke off flow. With rotodynamic pumps, this increases the system hydraulic losses and markedly decreases the pumping efficiency. A more efficient reduction of yield can be achieved by fitting a bypass valve to return part of the pumped flow back down the borehole thus decreasing the output without increasing hydraulic losses. However, the growth in mechanical and electronic variable speed devices (VSDs) provides a much more efficient method to control both the head and yield performance of diesel and electrically powered rotodynamic pumps. Apart from offering considerable energy savings, VSD motor technology should encourage the continuous steady operation of submersible pumps at reduced loads. This will extend the life of the pump and motor bearings. It also reduces the number of start-up and stop cycles that shorten motor life.

Positive-displacement VSD pumps coupled with transducers can provide the steady-state drawdown as needed to control saline interfaces and for skimming of thin aquifers. Combining the two main forms of renewable energy, wind generators and solar power with VSD pumps should enhance the performance of these systems.

Re-writing or delegating the legislative framework

The scope for governance that exist at the point of abstraction shows regulation of groundwater abstraction is often confounded by being asked to encourage access and volume on one hand and judging when the regulated abstraction becomes 'unsustainable' on the other. For example the Millennium Declaration charges regulators: *"to stop the unsustainable exploitation of water resources by developing water management strategies at the regional, national and local levels, which promote both equitable access and adequate supplies"*. However, under inherited colonial legislation or deliberate policies, regulators have to work with intractable common-law-based rules of capture. This *de facto* private ownership will continue to attract state-of-the-art drilling and pumping technology to achieve private profit without reference to the common-good objectives of modern resource governance. Establishing the appropriate administrative level for defining and enforcing a legislative framework shows strong and effective governance regimes are best based at community management level. In the drier States of Texas and New Mexico in the USA, the rule of capture remains in force but the responsibilities to virtually full adherence to the Millennium Declaration are forced down to the local Groundwater Management District (GMDs) level. This local regulation is seen to be more responsive to changing conditions than a State-wide regulation regime. Other examples of users controlling groundwater abstraction are seen to be driven by one of three factors – declining groundwater levels, declining yields or saline intrusion – or by all three. Most self-management examples are based on user groups that concentrate on collective exploitation and apply restrictions on individual users.

Future technological developments

The development of more precise and energy-efficient pumping technologies indicates that groundwater abstraction will continue to expand. Low-lift and low-output devices will continue to be needed to service low-intensity abstractors. However, the adoption of higher-capacity technology for high-value productive uses is likely to concentrate intensive abstraction from aquifers that are already at risk. Unless restricted by external controls, past experience shows any efficiency gains achieved in groundwater pumping for irrigation tend to be taken up by an expansion of the cultivated area.

Future advances in pump technology may be catalysed by the practical use of two materials that may impact on long-term electrical developments: these are superconductors and graphene. Superconductive materials generate very strong magnetic fields, so if they become commercially available, electric motors will be smaller, more efficient and more powerful. While graphene nanotubes have certain superconductivity properties, more immediate graphene applications are in photovoltaics. These have the potential to provide cheaper solar power generation. Other electric power developments already in use are super-capacitors to replace batteries. Currently their storage capacity is around 50 percent of that of batteries but they can be recharged in minutes and have a recycling efficiency of over 95 percent. Future developments in this field are expected to find wide application in the storage of electricity generated by solar and wind power.

Thematic Paper 8

SOCIAL ADOPTION OF GROUNDWATER PUMPING TECHNOLOGY AND THE DEVELOPMENT OF GROUNDWATER CULTURES: GOVERNANCE AT THE POINT OF ABSTRACTION

By

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Acronyms

AD	*Anno Domini*
asl	Above sea level
BC	Before Christ
BESCOM	Bangalore Electricity Supply Company, India
bgl	Below ground level
BP	Before Present
CFD	Computational Fluid Dynamics software
CILSS	*Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel*
CGWB	Central Groundwater Board of India
CWSA	Ghanaian Community Water and Sanitation Agency
DEFRA	Department for Environment, Food and Rural Affairs
DfID	UK Department for International Development
DRUM	USAID Distribution Reform, Upgrades and Management project
DWA	Zambian Department of Water Affairs
DWID	Zambian Department of Water and Irrigation Development
EU	European Union
FAO	Food and Agriculture Organization of the UN
GCD	Groundwater Conservation District
GHG	Greenhouse Gas emissions
GMD	Groundwater Management District
IWMI	International Water Management Institute
IDWSSD	International Drinking-Water Supply and Sanitation Decade
JMP	WHO/UNICEF Joint Monitoring Program
MDG	Millennium Development Goal
NGO	Non-Governmental Organization
NORAD	Norwegian Agency for Development Cooperation
NSSO	National Sample Survey Organization of India
PPP	Public-Private Partnership
PWM	Pulse Width Modulation technology

SGS	*Société Générale de Surveillance*
SPV	Solar Photovoltaic water pumps
UK	United Kingdom
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNICEF	United Nations Children's Fund
uPVC	Unplasticized polyvinyl chloride
USA	United States of America
USAID	US Agency for International Development
USGS	US Geological Survey
VLOM	Village-Level Operation and Maintenance
VSD	Variable Speed Drive
WENEXA	USAID Water-Energy Nexus Activity
WHO	World Health Organization

Compilers Note

The concentration of examples of groundwater irrigation from India and from the High Plains Aquifer in the United States of America (USA) reflects the extensive availability of appropriate technical papers. The considerable work undertaken and reported on from other major groundwater-based irrigation areas has been examined but coverage from these areas is more fragmented. However, the available papers in many cases report similar situations developing across all groundwater basins in Europe, Asia, the Middle East, Africa, Australia and the Americas.

The detailed role of pump-user management groups has not been specifically examined as these are seen as constantly evolving. The schemes are seen to expand, mature and decline as the social structure of the communities alter under the influence of external and internal political and economic developments.

1. Introduction

The last ten thousand years have seen water supply technology developed from the collection of surface water from rivers and ponds and groundwater from springs and wells in basic containers to complex pumped-piped distribution schemes. During the first nine thousand years, water resource developments and social regulation were aimed at satisfying domestic and irrigation supplies. The last few hundred years, however, have seen rapid advances in pumping technology that have outstripped the social adjustments to the rules governing the use of the resources.

Mankind was initially concerned about building effective groundwater-pumping machinery. However, once suitable technical and social solutions were developed, the impacts of large-scale groundwater abstraction were soon found to require new measures leading to legislation and conservation of the resource.

Over time a variety of pumps and motive mechanisms were developed as set out in "Mine Drainage, Pumps, Etc." (Behr, 1896). This provides extensively illustrated descriptions of the latest technology at the end of the 19thcentury and has an appendix covering "Water-Raising Machinery for Irrigation or Land Drainage". It also describes compressed air-powered and air-lift pumps. Two Food and Agriculture Organization of the United Nations (FAO) monographs – "Water Lifting Devices for Irrigation" by Molenaar (1956) and "Water Lifting Devices" by Fraenkel (1986) – provide further comprehensive summaries of traditional and motorized water-pumping technology at the time of publication. The 1956 monograph concentrates on describing and costing traditional and mechanized low-lift surface-water pumps for rice irrigation, while the 1986 monograph expands coverage to the design parameters, operational efficiency and economics of wind-powered and motorized pumping systems.

The four methods available to abstract water vertically against gravity from a dug-well or borehole are:

- direct lifting of a fixed volume with a container – rope and bucket(s) including the multi-container Persian Wheel;
- positive displacement of a volume by the movement of a plunger or intermeshing rotating walls[1];
- rotodynamic propelling by rotating blades or impellers (Figure 1) – shaft and electric submersible pumps, centrifugal suction (initial water flow at right angles to direction of rotation axis), turbines (water flow parallel or at and acute angle to rotation axis) and educator jet pumps;
- differential pressure by lowering the density of a water column – airlift.

Since 1900, progressive developments in pumping technology and motive power have underpinned an ever-expanding worldwide use of groundwater for rural, urban and industrial water supplies, as well as for livestock, agricultural and irrigation purposes. The main developments driving this expansion were the introduction of reliable diesel and electric-powered, shaft-driven, multi-stage centrifugal pumps. These have since enabled deeper aquifers to be systematically exploited.

Between the publication of the FAO monographs in 1956 and 1985, two highly significant developments in groundwater pumping became established. The first was the initiation by donor agencies and international lending institutions of large-scale hand-pump-based rural water supply programmes aimed at meeting the 1977 Mar del Plata (Argentina) Action Plan that led to the declaration of the 1981-1990 International Drinking-Water Supply and Sanitation Decade (IDWSSD).The second development was the evolution and rapid expansion in the use of electric submersible pumps for groundwater-based urban water supplies and irrigation. Large-scale

[1] Dating to the 3rd century BC the force pump used a plunger to press water out of a cylinder. Plunger pumps require a non-return valve and can be mounted at the surface and rely on suction and air pressure to lift water to the surface and therefore have a maximum possible lift of less than 10 m. Plunger pumps set below the water surface in the well directly lift the column of water in the rising main, and the lift capability depends on the power available and the strength of the materials used to construct the pump. Both forms of plunger pump were in use by the 15th century AD. The rope or chain pump pulls a continuous string of plungers though guide and lifting pipes. Diaphragm pumps rely on displacement of a flexible membrane. Rotary progressive cavity pumps are in common use (Mono Pumps) but gear, screw, eccentric vane and squeeze pumps have more limited application.

submersible pump groundwater irrigation took-off with the introduction of the centre pivot in Colorado in the 1950s (Kepfield, 1993).

In many countries, the adverse impact of this growth in use of submersible pumps on groundwater levels and/or quality triggered the need for legislation to regulate abstraction. The introduction of appropriate legislation, however, has been uneven given the population and economic demands placed on the groundwater resource base. In some cases, current legislation is conflicted by the impact of government subsidies and promotion to encourage further groundwater abstraction as typified by the biofuel market.

This thematic paper examines the historic and on-going development of water-lifting technologies and the governance problems and solutions that have arisen from controlled or uncontrolled groundwater abstraction. It also examines legislation on improved pump efficiency and the economics and life-cycle costing of borehole pumps.

2. Styles and Patterns of Groundwater Access and Use before Mechanized Drilling and Lifting

The development of steam power at the end of the 17th century marks an appropriate break in the development timeline for pumping technology. It also marks the point where direct-lift pumps were largely replaced by rotodynamic pumps that effectively propelled water upwards.

Pre-17th Century Developments

From the start, humans relied on open access to springs, river baseflow and shallow groundwater stored in sandy dry riverbeds as their main dry-season water sources. It is, therefore, reasonable to assume early humans established strategies to ensure safe access to these water supplies. There is evidence of their limited means for collecting and transporting water. Until recently, the Australian Aboriginal cultures with no ceramic technology used animal skins, delicately folded and stitched leaves, tree bark containers, wooded bowls and sea, egg and coconut shells as containers.

Society's systematic exploitation of groundwater for domestic and cattle watering coincided with the transition from forager to sedentary farmer. This followed the domestication of livestock and food plants between 9 000 and 11 000 years BP. Water availability was central in determining human settlement patterns. The group of 5-m-deep water wells of this age uncovered in Cyprus and elsewhere in the Eastern Mediterranean Region reflects a certain understanding of shallow groundwater occurrences. This was likely linked to experience gained when mining of flints and, later, metallic minerals for tool making. The establishment of settled farming inherently engendered the concepts of individual or communal ownership of land and water points that required protection by physical force or a system of customary law.

Archaeological evidence shows the rapid diffusion of all forms of technological advances across North Africa, the Middle East, Arabia, Western Asia, the Indus Valley and beyond between 10 000 to 4 000 years BP. Parallel technological developments occurred independently across Eastern Asia and South America. By 4 000 BP, wood-lined hand-dug water wells were in routine uses for community water supplies.

Under differing regional climatic regimes, three main forms of land use evolved:

- Dry land (rain-fed) arable farming developed in the tropical and temperate humid zones.
- Surface water irrigation spread along the major river valleys around 8 000 years BP and more localized pockets of groundwater spring based irrigation developed in the more arid parts of Southern Arabia and along the Persian Gulf.
- In the sub-humid and semi-arid zones, nomadic pastoralists relied on seasonal vegetation cover and on surface and groundwater sources.

Ample surface and groundwater sources are found in rain-fed farming areas and potentially supported the high population densities as seen in the African Lakes Region.

In the tropical arid and semi-arid zones from North Africa to Central Asia, a weakening of the southwest monsoon around 5 700 BP caused a regional decline in precipitation. The climate shifted from sub-humid to semi-arid and arid, and the woodlands and savannah grasslands across a broad swath of the northern Sahara Desert retreated. The pastoralist and dry-land farming population moved east to the Nile Valley where they merged with a fast developing surface water irrigation farming culture that mirrored the cultures in the Tigris-Euphrates Valley and the Indus Basin (Bazza, 2007).

2.1 Lifting water through direct human and animal energy

Between 4 000 and 2 500 years BP, many of the traditional man-, animal- and water-powered low-lift devices to support the surface water irrigation were invented: the water was moved by lifting or paddling. The earliest and most widely used lifting device from 2 000 years BC was the shaduf, which was supplemented by Archimedes Screw around 100 BC. The use of a bucket and rope to lift water undoubtedly has the longest history, and its use in water wells was improved by the introduction of the windlass. These irrigation-based early societies implemented appropriate protocols and laws covering distribution of the surface water resources and maintenance of the supply systems. The bulk of the irrigation relied on the rise and fall of the river, with annual floods diverted into canal systems from where the water was allowed to flow by gravity or was lifted onto the surrounding fields.

The post 5 700 years BP decline in precipitation was accompanied by increasing unpredictability in the climate. Across southern Arabia and down the Pacific Coast of South America, the areas under irrigation declined steadily until the mean catchment precipitation fell below 70 mm at which stage irrigation was no longer viable. Populations were forced to withdraw to those areas where they could exploit spate floods and groundwater for irrigation. This is possibly best seen in the archaeological record of southern Arabia. Here Harrower (2006) provides a detailed account of archaeological research into the ancient spate irrigation systems dating from the mid to late 6 000 years BP in the Wadi Sana' that drains the Southern Jol in Wadi Hadhramaut-Massila Catchment, South Yemen. Extensive Neolithic tool-making sites and cattle remains dated to 7 000 years BP point to an ancestral pastoralist culture that was supplemented by spate flood diversion systems and spring fed irrigation until climatic conditions deteriorated about 4 000 years BP.

Similar developments can be traced along other Wadi Hadhramaut tributary valleys and to the East in Dhofar, Oman. Here, water wells at Shisur and Ma Shedid in Wadi Ghudun supported the agricultural developments centred on the ancient city of Ubar. There is a hiatus in the archaeological record in the Hadhramaut from 4 000 to 3 000 years BP. Following this there is evidence that shallow groundwater wells started to be used for extensive irrigation farming along the main Hadhramaut Valley. At present, there are still appreciable spring flows from the Umm er Radhuma Limestone supporting irrigated farming in tributary valleys, Wadi Ain, Wadi Idm (Ardar Raydah) and Wadi Sana'.

The implementation of irrigation systems must have rapidly progressed from an individual task to a collective undertaking that allowed the worldwide emergence of the early city-states. Prior to the spread of the Abrahamic religions, the religious and civil leadership powers of the surface water irrigation cultures were held by god-king-priest ruling elites who tightly controlled all aspects of the rights to land and water ownership. Many of the earliest written records of these irrigation-based societies concerned water rights and responsibilities for maintenance of the water capture and diversion structures. The situation regarding groundwater other than that developed by the qanat systems was largely outside the interest of the ruling elite. Thus, the early laws regarding groundwater centred on the private ownership of the land and the hand-dug wells. In many cases, the principles behind these laws have been largely carried over to the present day.

2.2 Mobilising gravity and drainage

The development of horizontal infiltration galleries to exploit groundwater from extensive mountain front outwash fans started around 1 000 BC in northwest Persia where they are known as qanat. They rely on gravity drainage (Mohammed Karaji, ca. 1100 AD) and likely were developed from observed groundwater flows that occurred when horizontal copper mine adits were driven into the water table. Although length and depth of an average qanat are respectively around 5 km and less that 200 m, some may be considerably greater, reaching 70 km in length and 350 m in depth (Yazdi, 2006). During the Achaemenian period (550-330 BC) qanat construction was subsidized by tax relief: this benefit was reinstated during the post 621 AD Islamic Period when many of the qanat were controlled by the local government under formalized rules as set out in the "Alghani" – The Book of Qanat (Yazdi 2006). These included a minimum separation distance of 375 m between two qanats.

Qanat technology was transferred from Persia to hydrogeologically favourable sites in the Near East, Central Asia, North Africa and Southern Arabia (Lightfoot, 2000). Here they are known under a variety of names: *falaj* (Oman), *karez* (Afghanistan, China, Pakistan) and *foggara* (North Africa). These terms, however, frequently describe spring-capture structures and the downstream water channel with no underground infiltration gallery. The peak of qanat development occurred between the 16th and 18th centuries when more than 380 000 were recorded in the Hamadan, Isfahan and Tehran regions (Yazdi, 2006). Yazdi also reports that 34 355 qanats were still in use during 2003-2004 with a combined yield of 8.2km^3/year.

2.3 Rules of the game under low intensity abstraction

The archaeological record shows the earliest pastoralist cultures freely exploited amply watered rangelands and adopted small-scale rain-fed cropping. The grazing areas of the more arid areas of the Near East are seasonal and localized. This forced the pastoralists to adopt a nomadic lifestyle. However, they benefited from a favourable distribution of perennial rivers and springs for watering livestock that were supplemented with surface storage tanks and hand-dug wells. Most of the winter-grazing grounds were on the lower slopes of the mountains that flanked the lowland drainage basins close to the well-regulated centres of irrigation farming. These provided a ready market for the pastoralists' flocks of sheep and goats. Over time, pastoralists acquired formal rights to the winter grazing lands and access to water. Both pre-Islamic and Islamic laws recognised and protected these rights.

The rangelands of the semi-arid Sahel and the Horn of Africa have more limited surface water sources. Here pastoralists rely on springs, water harvesting structures and hand-dug wells that have been in use essentially unchanged throughout the archaeological record. Some were, and are, of substantial size and required regular communal maintenance inputs. Established by 7 500 years BP, the pastoralist and small-scale subsistence farming communities resisted or accommodated external influences that could have impacted on their stable social system of land use. This level of social stability is reflected in a long oral and written tradition as a series of city-states rose and declined from the 5th century BC onwards. Traditional rights to groundwater were centred on the collective clan tenure of lands and hand-dug wells. In many cases, the principles behind these rights have been largely carried over to the present day as typified in the Oromo-Borana customary lands in Ethiopia and North Kenya (Box 1). Across the Indian sub-continent, the step well that came into use around 200 AD is a more highly engineered version of the Borana *"tula"*.

2.4 Mobilising wind energy

The first use of wind power appeared around the 4th century AD in Europe and China and the use of horizontal sail windmills to pump water for irrigation was recorded in Afghanistan and Persia by 700 AD. In the 14th century AD, vertical sail windmills were in use for drainage in Holland but these had a very limited lift capacity (± 1m). The discovery of metal working prompted the use of bellows and fans to pump air for smelting and mine ventilation. These provided the blueprint for some of the first water pumps. Cylinder plunger pumps with packed seals were introduced in 1675.

By the end of the 17th century, many forms of low-lift devices were employed for pumping surface water for irrigation and domestic supply purposes. The options for meeting higher lifts required for abstracting groundwater from hand-dug wells or natural caverns were limited to using rotating devices fitted with a single or a multiple series of containers as typified by the Persian Wheel (*Saqiya*). At that time, it is reasonable to state that individual owners and communities were largely responsible for looking out for their own water supplies in terms of ownership.

2.5 Suction pumps – Low-lift agrarian societies

As engineering and metal working improved during the 18th century, effective lever-action cylinder hand-pumps came into wider use for lifting water from hand-dug wells for domestic purposes and they became central to meeting the demands of rapidly growing urbanized communities. However, with underground mining needing to move greater volumes of water, the18th and 19th centuries also saw a shift from pure lifting

Box 1: Oromo Wells, Ethiopia

The Oromo have strong homogeneous culture and social order based on age groups (*Gada*). Covering large areas of Ethiopia and northern Kenya, the land they occupy lies in a range of agro-climatic zones. They have ancient collective democratic traditions that enabled them to practice sustainable land use, underpinned by the concept of a proper and equitable distribution of arable and grazing lands.

The Borana are one of the major pastoralist groups of the Oromo. Their rangelands occupy the semi-arid parts of the Sidamo Region in southern Ethiopia and the more arid Marsabit Region of northern Kenya. The underlying beliefs of the Oromo are illustrated by this extract of a traditional poem about mother earth:

Upon you there is food.
Under you there is water,
We graze our herds on you.

To effectively manage the resources of their semi-arid and arid rangelands, the Borana employ rain-water harvesting, spring sources and hand-dug wells in a way mirroring mankind's first endeavours.

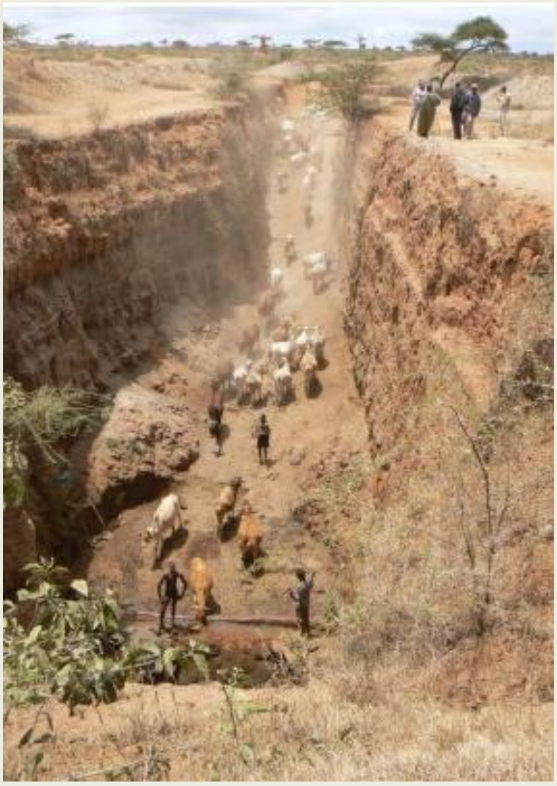


Figure B1-1 (left): Traditional Borana tula well, Sidamo Region, southern Ethiopia.
*Clusters of such wells are collectively clan-owned and maintained. The use is regulated by an appointed overseer (*konfi*) and in times of drought, tula can be jointly used by an alliance of clans that share the upkeep of the well and surroundings. Access to watering days at the tula is allocated according to an established schedule. (Gufu Oba, 1996; Skinner, 2010).*

Figure B1-2 (lower left): Traditional Oromo hand-dug well between Bora and Burka in northeast Ethiopia.
Water is collected using leather buckets thrown hand-to-hand to the surface from some 15 m below ground.

Figure B1-3 (lower right): Borana tula well located in a community 30 km south-southwest of Wachile, Sidamo, Ethiopia.
Google Earth Image (4º 16' 54N" 38 º 58' 30"S). Such wells have enabled the Borana to establish sustainable use of the available grazing across the rangelands.

of water to more efficient methods of pushing or impelling water against a head[2]. Based on advances in mathematical analysis, physics and metallurgy, practical designs for suction and positive-displacement reciprocating cylinder pumps started to be developed and patented. Among the theoretical advances were the definition of power in terms of rate of lift and weight by John Smeaton in 1752 and, based on Newton's laws, Leonhard Euler's mathematical analysis of centrifugal forces as applied to water pumping in 1754.

While the use of rotating fans for ventilating copper mines in Portugal possibly dates back to the 5th century AD, the concept for the centrifugal pump was set out by Italian engineer Francesco di Giorgio in 1475. The first centrifugal pumps with straight vanes appeared in the 17th century AD. Curved vanes developed by John Appold in 1851 were found three times more efficient than the straight vane centrifugal water pumps then in current use. Other developments around the same time were the introduction of the shrouded impeller, the whirlpool chamber and multistage pumps. The lifting heads achieved by centrifugal pumps, however, were constrained by the low shaft rotation speeds and the efficiency of the water seals[3]. The introduction of the vane diffuser in the last quarter of the 19th century saw a further increase in centrifugal pump efficiency.

2.6 Steam power – First motorised pumps and the beginnings of hydrogeological science

The parallel development of steam power saw, in 1712, the introduction of the Newcomen beam engine coupled to positive displacement pumps. Although initially used for mine dewatering, these pumps were soon in use for urban surface water supplies. The more fuel-efficient Watt steam engine was introduced between 1760 and 1775. This was followed by the high-pressure steam engine around 1800 and the rapid introduction of a wide range of steam powered applications for industrial manufacture, railway locomotives, paddle wheel and screw driven ships. These demanded lighter, higher powered and faster engines. Stationary high-powered long-stroke engines had a wider application in water pumping as typified by the installation of the Kew pumping station on the River Thames upstream of London in 1837.

By the early 1800s, the main principles of geology were being established, and by the 1820s the basics of groundwater flow and occurrence had been defined in France, including an understanding of the artesian Paris Basin. Picked up by British geologists, this knowledge was applied to the artesian London Basin and opened up the possibility of future large-scale groundwater abstraction for urban water supplies.

As worldwide urban and industrial growth polluted the immediate surface water sources during the first half of the 19th century, newly established water supply companies turned to investigating and developing alternative groundwater resources. As part of a technical proposal to augment London's surface water supplies using groundwater from the Cretaceous Chalk aquifer, Mylne (1840) reports that the construction of artesian boreholes in the London Basin had become widespread. The wells were typically several metres in diameter and often had additional horizontal headings or adits. Supporters and objectors to this development demonstrated an understanding of the cone of depression around an abstraction well and the seasonal variations in groundwater levels in response to recharge (Stephenson, 1841; Clutterbuck, 1842, 1843 and 1850).

Many early urban supply schemes relied on overflowing artesian groundwater and there was no immediate need to turn to pumps. In London, 120-m-deep wells commissioned in 1844 powered the Trafalgar Square fountains until around 1890 when the declining artesian pressure had to be augmented by pumps. The decades following the 1850s saw rapid growth in urban populations and when, in 1854, John Snow demonstrated the Broad Street water well as the source of a major cholera outbreak in London, metropolitan authorities worldwide responded by commissioning and putting in place, large-scale water supply schemes based, in part, on groundwater. In North America, the majority of the urban groundwater supplies were taken from unconsolidated alluvial sands and gravels. In Europe, attention focused on pumping groundwater from consolidated sedimentary aquifers. This expansion created a demand for improvements in pump capabilities in terms of discharge and head.
With the introduction of steam-traction engines in the 1850s, farmers and miners had mobile power plants to drive a variety of water pumps for drainage and lifting purposes. The use of steam traction engines continued

[2] For the purposes of this paper the term "head" covers both the total physical distance water is lifted plus the hydraulic pipe losses.
[3] The pumping head capability of all rotodynamic pumps is a function of the impeller tip speed.

well into the 1930s. In addition, the powerful commercial DC and AC electric motors introduced in the mid-1880s were quickly adapted by pump manufactures as substitutes for existing steam engines and then for purpose-built belt-driven pumps. By the mid-1890s, reliable internal combustion engines were adopted to power both reciprocating cylinder and centrifugal pumps for water supply. In agricultural areas, motorized pumps began to augment the windmills that were in wide use for domestic and livestock water supplies and irrigation.

As the 19th century closed, engineers had produced very robust positive-displace pumps capable of lifting 10 000m^3/day to 150 metres and less reliable rotodynamic pumps capable of moving 2 000m^3/day but with a lift limited by the shaft seals to a few metres. Most expanding urban water companies constructed large diameter shafts and installed very large beam engines cylinder pumps to abstract groundwater. In many urban areas, the increase in public and private water supply abstraction had already resulted in significantly lower groundwater levels.

Away from Europe and the USA, some urban communities continued to rely on traditional groundwater sources. Qanats continued to supply many cities in Iran. The use of open hand-dug wells continued to supply many towns and villages with animal- and man-powered lifting devices. For example, groundwater was lifted from wells tapping the shallow aquifers of the Wadi Tuban at Sheikh Othman to an aqueduct feeding the port of Aden in southern Yemen as late as 1914 (Connelly, 2005).

3. Twentieth Century Developments

3.1 Shaft-driven pumps – From mines to agriculture

Between 1901 and 1920, in America, specialist pump-manufacturers' attempts to satisfy the new groundwater irrigation market in the Mid-West and Pacific Coast States with high-volume, low lift and line-shaft centrifugal suction pumps was slow to take off. In Nebraska[4] this was largely due to the speculative nature of the investment in irrigation farming (Kepfield, 1993). The farmers found that under the prevailing economic conditions, there were too many risks involved in changing from their existing windmills and reciprocating pumps.

Prototype line-shaft turbine pumps were developed in 1897. These were quickly followed by the first commercial pumps in the early 1900s as several California manufactures saw the opportunity to satisfy the demand for high-yield pumps that would fit in small diameter water wells. Faced with declining groundwater levels and increased drawdowns as the use of these pumps grew, the manufacturers concentrated on improving the hydraulic efficiency and material quality of their pumps.

By 1920, the three main types of rotodynamic pumps – radial, mixed and axel flow – were in use (Figure 1). The essential components of the high-lift line-shaft pumps, the discharge head, the vertical drive shaft and support bearings and the centrifugal impellers and housing had been largely perfected. The introduction of the gear head pump drives enabled direct coupling of internal combustion engines and electric motors to high speed pumps.

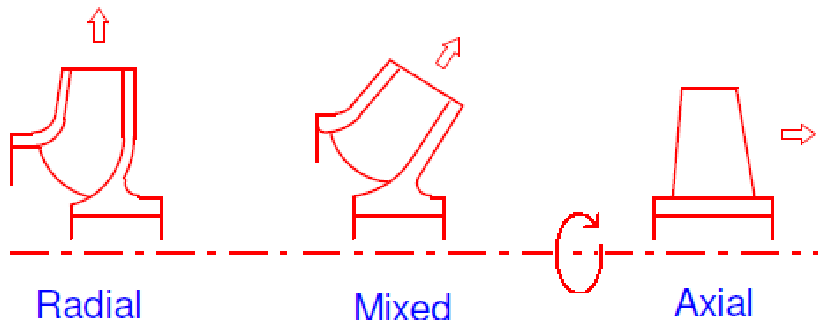


Figure 1: Basic classification of rotodynamic pumps (reproduced from BPMA, 2006).

3.2 The beginnings of groundwater irrigation – The High Plains Aquifer, USA

The take up by irrigation farmers in Nebraska in the 1920s remained low with irrigated lands beginning to extend up the interfluves from the shallow groundwater areas close to the main river valleys. Despite this reluctance to invest in new pumps due low grain prices, a minor drought in 1925-6 showed the advantages of groundwater based irrigation and by 1930 over one thousand pumps were used to irrigate some 12 000 ha In Nebraska (Box 2).

According to the 1930 census of Irrigation Districts in California some 100 000 ha of land was irrigated using 420 Mm^3 per year of groundwater pumped from wells (equivalent application 420 mm/year). This was about 15 percent of the total water diverted for irrigation and domestic supplies in the State. The USA Census data (Box 3) clearly reflects the major changes in the groundwater irrigation scene in the 19 main irrigation States as electric powered line-shaft turbine pumps became dominant. These changes were largely dictated by the 5-to-10-m decline per decade in groundwater levels across most irrigation areas.

From 1930, the introduction of higher performance line-shaft pumps, movable sprinkles and gated pipes, couple with cheaper high-speed petrol engines, lowered the costs and improved the reliability of irrigation. This led to an accelerating expansion in groundwater irrigation (Green, 1992). The impetus was further driven

[4] The State of Nebraska is cited as an example as it ranks first in the USA for groundwater-based irrigation.

Box 2: Nebraska Growth of Groundwater Usage

The timetable of groundwater development for irrigation in Nebraska, USA, illustrates the interplay between government policies, economics, pumping technology, environmental impact and legislation. Surface water irrigation in the State started in the 1850s and by the 1960s, the surface-water-irrigated land covered about 400 km^2. Following droughts between 1883 and 1895, the State of Nebraska introduced laws governing the right to use surface water based on a *"first in time, first in right"* principle. The 450 000 km^2 High Plains Aquifer underlies parts of Nebraska, South Dakota, Wyoming, Colorado, Kansas, New Mexico, Oklahoma and Texas, in mid-western USA (Figure B2-1). Although large sections of the area are underlain by numerous oil fields, agriculture is the dominant economic activity. The High Plains Aquifer outcrop in Nebraska covers 130 000 km^2 and supports 3 000 to 3 300 km^2 of groundwater irrigation making it the largest State user in the USA.

Between 1901 and 1920, as mentioned earlier, American pump manufacturers' attempts to satisfy the new speculative groundwater irrigation market in the Mid-West and Pacific Coast States with high-volume, low-lift and line-shaft centrifugal pumps largely failed partly due mainly to unreliable belt drives and lack of suitable high-speed power units. In addition, irrigation farmers did not have access to the skills necessary for maintaining pumping equipment.

In Nebraska by 1928, the impact of groundwater irrigation on the water table along the Platte Valley was sufficient to dispel the idea that the resource was unlimited, and the State was called on to survey the resource. Published in 1943, the resulting report included mapping of the groundwater resources. On the other hand, rural electrification was a central programme to the 1935 American New Deal and the percentage of farms in Nebraska with electric power rose from 9,7 percent in 1919 to 95 percent by 1954.

Manufacturers were quick to produce electric-powered in-line shaft pumps. These were more efficient and easier to maintain than gasoline pumps and more consistent than windmills. This, coupled with pump-purchase credit plans prompted a rapid expansion in groundwater irrigation and by 1940 the State found it necessary to introduce new legal and technical management measures.

Subsequently these were revised as natural conditions became better understood and demands on the resource changed. The first revision, passed in 1957, covered the registration of irrigation wells and placed a minimum 200 m well spacing. In 1969, legislation was consolidated under a bill establishing Land and Water Conservation Districts. The Groundwater Control Act passed in 1975 was supplement by the1996 Act (Legislative Bill 108) covering the integrated management of hydrologically connected groundwater and surface water.

The widespread introduction of the centre pivot irrigation spurred the main growth of groundwater irrigation from 1960 to 1980. This period gave rise to the philosophy of the USA water well drilling industry: "we drill water wells to sell pumps". After 1980, farm profits fell due to low agricultural commodity prices and rising pumping cost caused by declining groundwater levels. Since then most economic studies show groundwater irrigation to have negative returns without the receipt of external subsidies (Gilson *et al.*, 2001). In 1988, agricultural economists projected a slow withdrawal from irrigated farming to dry-land farming as the water table declined, and new investment in wells and

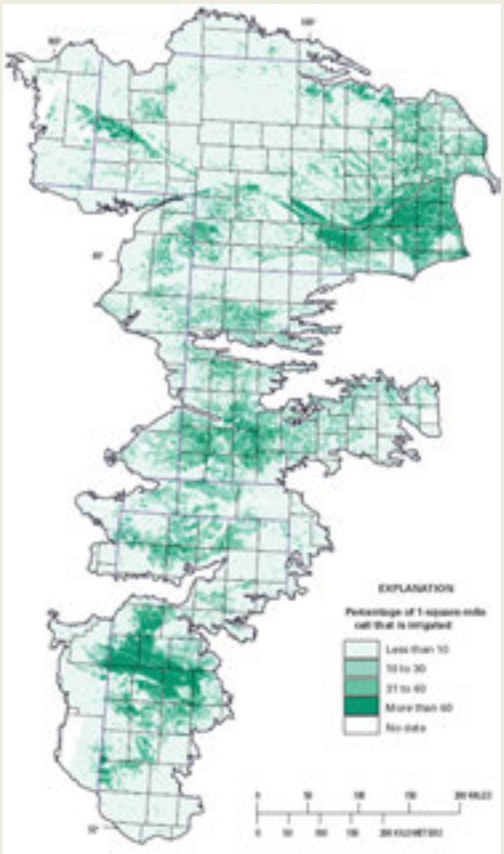


Figure B2-1: High Plains distribution of irrigated lands (adapted from Litke, 2001) irrigation equipment became uneconomic (H. P. Mapp, 1988).

The area under irrigation from 1980 to 1998 was stabilized by a variety of federal subsidies and tax breaks, including resource depletion relief and guaranteed crop prices. Between 1998 and 2001, increased subsidies covered a dip in commodity prices and boosted the farming economy across the High Plains. In addition, targeted subsidies to encourage soya-based biodiesel production were introduced in 2002, followed in 2005 by more emphatic subsidies for the production of grain crops for ethanol biofuels. In 2007, the USA declared a nationwide target of 133 Mm^3 /a bio-ethanol production by 2017. To achieve this, further subsidies and easing of land use restrictions were introduced (Water Science and Technology Board of the National Research Council, 2007). The Environment News Service (ENS, 2007) estimates 4 Mm^3 of process water is required to produce 1 Mm^3 of bio-ethanol on top of the irrigation water demand required to produce corn feedstock.

by the 1930-36 "Dust Bowl" drought that affected most of the Great Plains area of North America lying to the West of the 100th meridian. The rapid expansion in rural electrification under the "New Deal" saw widespread phasing-in of electric motor-powered pumps and by 1944, over 5 150 groundwater irrigation areas covered some 100 000 ha in Nebraska (Condra, 1944).

Box 3: Extracts from the United States Department of Commerce, Bureau of the Census, 14th, 15th and 16th Census (1920, 1930, 1940) of the United States: Irrigation of Agricultural Lands

Covering the 19 irrigation States (Arizona, Arkansas, California, Colorado, Idaho, Kansas, Louisiana, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington and Wyoming), the census data shows the steady growth in the number of wells and groundwater usage. It shows the transition from centrifugal to turbine pumps and the rise in the use of electrical motors. Also notable are the decline in steam power and the declining trend in overflowing artesian wells (the post 1900 impact of the artesian Dakota Sandstone Basin peaked in 1910-1914 and is seen to be declining by 1930 and is unremarked upon in the 1940 census).

Table B2-1: Data from 1930 Census

	Flowing Wells	m^3/sec	Pumped Wells	m^3/sec	Pumps	m^3/sec	Motors
Pre 1860	9	0.02	75	3.84	101	5.68	89
1860-69	21	0.02	54	1.55	78	4.69	72
1870-79	107	0.41	82	4.31	115	51.61	105

1880-89	513	2.47	260	11.21	373	81.52	338
1890-99	319	1.35	610	27.19	714	0.17	623
1900-04	426	4.08	794	28.57	990	186.56	916
1905-09	396	7.07	1704	83.34	2 075	339.70	1 911
1910-14	677	7.36	5371	198.52	5 940	375.19	5 602
1915-19	517	2.62	6623	269.78	8 468	599.59	6 961
1920-24	572	3.62	7902	288.15	7 216	419.05	8 258
1925-29	532	4.48	10829	396.16	11 551	508.92	11 551

Table B2-2: Data from the 1940 Census

	1920	1930	1940
Number of Pumped Wells	32,094	56,729	88,279
∑ Potential yield m^3/s	1160.6	2048.3	2735.3
Electric motor	289,018	876,186	1,118,024
Internal combustion engine	259,615	265,756	588,123
Water	8,093	12,058	-
Steam	10,768	872	-
Other*	125,429	50,343	56,540

Table B3-3: Data from the 1920, 1930 and 1940 Census

	1920	1930	1940
Centrifugal	581 274	726 301	597 057
Turbine	24 390	302 294	901 157
Rotary	36 716	118 856	
Reciprocating	32 344	5 338	
Air Lift	10 072	1 627	
Plunger		17 503	17 558
Screw		8 732	
Water Wheel		285	
Bucket		117	
Scoop Wheel		45	
Other/Mixed*	143 307	50 343	56 540

* Other and Other/Mixed largely implies a combination of pump types and/or power plants were in use.

3.3 Growth of groundwater-based urban water supplies

The demands of the urban water supply and mine dewatering markets at the beginning of the 20thcentury were largely satisfied by the existing high-head, high-volume, beam-reciprocating cylinder pumps. Although inefficient, these users valued the reliability and robustness of these machines and extended their use into the 1950s. With the recognition of biological pollution of groundwater, the first step in protecting urban groundwater supplies In the United Kingdom (UK) was the Margate Act of 1902 that empowered water boards to establish 1 500 yard (ca. 1360m) protection zones around their abstraction wells (Thresh and Beale, 1925).

Severe droughts in southern England between 1932 and 1934 prompted legislative moves in the UK and the establishment of a Water Unit within the British Geological Survey in 1937. By this time, with over 750 wells abstracting some 10 000 m^3/day within the London area, groundwater levels had declined from 15 to 45 m under the North London pumping stations of the Metropolitan Water Supply (Walters, 1936). The perceived mounting water resources deficit was addressed in the UK Water Act of 1945. This initiated a broad assessment of the Nation's water resources. In addition, the water companies began wholesale replacement of steam-powered groundwater-pumping machinery with electrically-powered close-coupled line-shaft pumps.

From the 1850s to the mid-20th century, expansion of the railways in South America, Africa, Australia and Asia was heavily dependent on groundwater wells for boiler water. These encouraged a rapid spread of drilled wells and pumps. For example, the boreholes drilled in Zambia between 1902 and 1908 for the railway connecting Livingstone to the Copperbelt discovered the prolific Lusaka dolomite aquifer, and the earliest private borehole recorded in Lusaka, Zambia, dates from 1909. Equally significant is the fact that the sites for the new capital cities in Zambia and Tanzania (Dodoma) were largely selected on the basis of recently discovered groundwater resources.

3.4 Electro-submersible pumps – Self-supply and the race to deplete

Manufacture of waterproof electric motor pumps began around 1904 and until the 1940s, the term submersible motor and pump was largely applied to sump and bilge pumps that worked under water. In the mid-1940s, the use of the term changed to describe the close-coupled electric submersible borehole pump configuration. With the introduction of powerful, high-speed, submergible electric motors and effective high-pressure shaft seals, specialized pump manufacturers developed high-lift centrifugal and turbine pumps fitted with diffusers for mine drainage in the 1930s. This enabled deeper underground mining below the regional water table as typified by the lead and zinc Broken Hill Mine at Kabwe, Zambia.

Prior to the 1930s, manufacturers frequently used models and prototypes to perfect the design of centrifugal and turbine vanes, impellers and shrouds. Using these methods, designers were able to produce pumps with specific yield and head performance curves. In 1932, hydraulic research that showed previous visualization of frictionless non-viscous water flow failed to represent the actual velocities and flow paths generated by rotating pump impellers (Fischer and Thoma, 1932). This research provided a base for future perfection of submersible and line-shaft pumps. Cavitation damage to impellers was seen as a major wear factor associated with excessive vane tip speeds.

The 1930s also saw the introduction of the line shaft driven progressive cavity pumps. Technically, therefore, from around 1930, with a range of purpose designed borehole pumps and versatile well drilling machines, planners and investors had worldwide access to groundwater as typified by the groundwater development in Wadi Hadhramaut in South Yemen for the piped Tarim urban water supply commissioned in 1932.

3.5 First groundwater governance initiatives

By the middle of the 20th century no management or legal constraints had been placed on the construction and maintenance of water wells or the installation of pumps beyond the community management as typified by the Oromo in Ethiopia, the recognition of traditional water rights under Muslim Law and the creation of protection zones around public water supply wells.

Almost all users, from individual householders through irrigation and dry-land farmers to urban water supply and industrial companies had full confidence in their installed groundwater pumping equipment in terms of reliability and durability. Having had a role in selecting the equipment, they understood and accepted the operation and maintenance demands involved in the use of pumps. While for most of the general public the majority of groundwater developments stemming from these advances had largely taken place unnoticed and unremarked, there was a degree of awareness among groundwater experts of their lack of understanding of the resources being exploited. This awareness was sharpened in countries with recurrent droughts and expanding demands from growing populations and economies. It also brought existing water rights legislation into question as society adopted the view that groundwater was a common property resource. This view led to refocusing of legislation aimed at ensuring the security of supply for right holders. This required a much sounder understanding of the groundwater resources than had previously been necessary.

To fill this knowledge gap in North America and Europe, the responsibility for monitoring and evaluating of groundwater was vested in the National and State Geological Surveys or Water Resource Agencies. The first step in the UK was the1945 UK Water Act. But by not treating the surface and groundwater as single entity, this Act failed to address the impact of increased groundwater abstraction on river flows in southern England. The 1963 Water Resources Act rectified this oversight and created a Water Resources Board charged with planning the integrated development and conservation of water resources on a national scale.

3.6 Worldwide expansion of urban and rural groundwater developments

Outside North America and Europe, taking advantage of ready access to small-diameter drilled water wells and line-shaft pumps, groundwater was the prime source for many of the first piped urban water supplies. By 1960, this pattern of groundwater development provided an estimated 50 percent of all urban water supplies to population centres of less than 100 000 in Africa, Asia, South America and Australia. In addition, groundwater dominated the development of rural water supplies.

In Africa, following European procedures, annual budgets were centrally allocated for the steady and systematic construction of hand-dug and drilled well programmes at sites decided at the district and provincial government level. Usually some 200 hand-dug wells and 100 to 200 boreholes (Table 1) were programmed countrywide in Southern and Central Africa (Box 4). Most boreholes were finished at 150 or 200 mm diameter and equipped with diesel powered reciprocating cylinder pumps until the 1960s when line-shaft progressive cavity pumps became more popular. The hand-dug wells were usually equipped with buckets and windlasses.

Rarely, groundwater developments for rural water supplies ran into unexpected problems. During the late 1950s and early 1960s, among unreported government groundwater-based rural water supply initiatives that should have impacted on the planning of future developments was the Colonial Government's Lake Kariba resettlement scheme in southern Zambia. Some 57 000 people were moved to new government constructed villages as their traditional Gwembe Valley homeland was flooded behind the Kariba Dam. At around 20 sites following resettlement, villagers were found to be suffering from severe fluorosis. Investigations showed the

Table 1: Summary of Groundwater Development Works, 1942 - 1952, Zambia (WDID, 1953).

Works completed	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	Total 1942-52
Boreholes	24	18	40	38	40	89	110	178	178	148	184	1 047
Total meterage	1154	973	2019	1570	1580	3415	4372	6294	6179	4966	6478	39 000
Hand-dug Wells	114	134	105	82	54	101	163	202	219	266	237	1 767

Box 4: Rural Water Development – Roots of Ownership and Sustainability

Based on an annual budget, the Pre- and immediate Post-Independence rural water development policy of the Zambian Department for Water and Irrigation Development (DWID) was driven by decentralized requests for improved water supplies originating from district level government committees. On receipt of the requests at regional level, the provincial DWID office undertook a feasibility survey that included an outline selection of the raw water source and preliminary costing. In practice, this approach was largely demand-driven with the Central Government supplying funds within its budget limitations.

A 1952 Report (DWID, 1953) records:

> *The concrete-lined well retains its popularity as a source for domestic water supply, and there is very little reduction in the demand for wells. It is worth noting that villages are now beginning to realise that the wells are theirs and that it is their responsibility to look after them. Wells are being kept in better condition, surrounds are being kept cleaner, and there have been fewer demands on the Department for well repairs, although the number of wells in use is much higher.*

The Report for the Southern Region goes further:

> *Very few wells were sunk by the Department in (...) rural areas. There is an increasing tendency for this type of work to be done by local well diggers, trained by the Department. The Department provides the materials and general supervision but the community supplies the labour.*

How rural development shifted from the above model to that described in the influential "Drawers of Water" (White, Bradley and White, 1972) represents a major fault line in the progress in implementing rural water supply. White, Bradley and White do not comment on this linkage between ownership and sustainability, but do suggest an approach to low-cost rural water supplies that features the same ideas:

> *Individual homeowners would be systematically encouraged to make independent improvements. These include individual cisterns, shallow wells, spring protection (...). Social guides would include research on new methods, information on improving techniques, and technical assistance in design and construction.*
>
> *Such a policy would depart from the current tendency to focus nation efforts on rural projects directly administered by national agencies. More emphasis would be placed on stimulating individuals and community groups to make their own improvements. (Page 267)*

At present it is valid to include donors and international development loan projects to national agencies in this comment. The natural wish of donors and development agencies to acclaim their works with prominent billboards at the entrance to endowed communities would seem to detract from engendering the necessary community ownership of the scheme and hence its sustainability. How much better to proclaim: *this village with the help of the xyz donor have installed their own water supply system*.

In the early 1990s, the World Bank indicated a return to a decentralized model for water supply development that embodied many aspects of the earlier Zambian DWID practices. In 1994, Zambia re-adopted decentralization and community-based projects (Harvey and Skinner, 2002), and now the Zambian Ministry of Local Government and Housing (MLGH, 2007) sets out the guidelines for community management of hand-pumps that implies total community ownership of the installations.

new water supply boreholes to have damagingly high fluoride levels. The government was forced to destroy the affected boreholes and again move the villagers to new sites. Subsequently, water samples from all successful government-drilled domestic supply boreholes were sent to the government analyst for full chemical determinations. Decades later, under another accelerated programme in Bangladesh, groundwater from the hundreds of thousands of tube wells sunk in the 1970s, 1980s and 1990s were belatedly found to contain poisonous levels of arsenic.

Although natural contamination of groundwater is uncommon and geographically localized, there are other recognized cases. The two examples of hazardous groundwater mentioned above suggest that proof of the acceptable chemical quality of any new source should be required in administrative procedures for the granting of water rights for domestic use and, possibly, during pump purchase.

3.7 Groundwater development – The perceived rural water supply solution

From the mid-1960s, with rising populations, the newly independent nations found a steady incremental expansion in rural water supplies politically unacceptable. Accelerated programmes were needed to provide clean drinking water that would improve the nations' health and welfare. To meet this demand, the international lending and development agencies focused on rural water supplies. Groundwater had long been identified as the prime source for improved rural water supplies with hand-dug and drilled wells fitted with hand pumps as the obvious route to implementing the programmes (Wagner and Lanoix, 1959; United Nations, 1960; World Bank, 1976; McJwikin, 1977; Hughes, 2000).

While virtually all externally funded development projects included counterpart training and institutional strengthening, in practice most national government organizations did not have the manpower resources or establishment to provide suitable candidates for training. This led to the projects concentrating on the technical execution of the work and the schemes subsequently proving unsustainable with local staff unable to operate or maintain the equipment. In detail, another significant problem with many accelerated programmes occurred and still occurs, when the installation of pumps in successful boreholes falls rapidly behind drilling progress until the time lag between well completion and equipping is measured in years (Box 5).

In Asia much of the work was undertaken with reasonable success by international consultants and private contractors. The first and second tube-well programmes in Bangladesh, for example, were funded by the World Bank's International Development Association. Elsewhere, the accelerated programmes were executed following European models within a receiving national government framework. The results were more mixed as the project design and programmes usually failed to take into account the local conditions, infrastructure and technical resources (Vaa, 1993). Classic examples include the access problems involved in moving 20-tonne drilling rigs though rural areas along tracks and over bridges designed for the 7-tonne trucks, farm tractors and trailers. Equally, the complexity of the drilling rigs and, even more so, the compressors were beyond the capabilities of the local mechanics. This was seen in an early, relatively large-scale UNICEF intervention in Pakistan that floundered as the receiving agency did not have the means and technical resources to deploy and utilize water supply equipment provided under the programme (Bayer, 1987).

3.8 International Drinking-Water Supply and Sanitation Decade (IDWSSD 1981-1990)

To rationalize a global approach to improving rural livelihoods by securing safe drinking water for all, the 1977 Mar del Plata World Water Conference Action Plan formulated plans leading to the UN International Drinking-Water Supply and Sanitation Decade (IDWSSD 1981-1990) with the objective to:"provide every person with access to water of safe quality and adequate quantity, along with basic sanitary facilities, by 1990." Executing this directive required coordinated action from both the supply side and the demand side.

For the first decade or so, the supply side – comprising the international and bilateral lenders and donors and the equipment manufacturers – dominated the field. The demand side comprising the beneficiaries – generally the national governments perceived as *de facto* representatives of their populations – were largely passive recipients. Given the scale of the task, close attention was given to the selection and price of equipment and materials (Weiss and Jequier, 1984; UNICEF, 1999). By the mid-1990s, the views of the community on the demand side – mainly from non-governmental organization (NGO) feedback – began to receive more attention (Carter, Tyrrel and Howsam, 1996).

Box 5: Unequipped Boreholes and Accelerated Pump-Based Rural Water Supply Programmes

The 1960 United Nations (UN) monograph “Large Scale Ground-Water Development” presents concise guidelines and advice to all professionals engaged on groundwater programmes. It covers the phasing of groundwater developments, organizational and technical requirements, and its appendices cover a range of pumping options. It stresses the staffing required for normal development activities and recommends calling in external consultancy to help cover emergency or accelerated programmes. The one not highlighted problem area, however, that continues to hamper most rural groundwater programmes is the hiatus between the completion of a groundwater abstraction borehole and the installation of a pump.

The American drillers’ view of their water well industry is summed up by their maxim: “we drill wells to sell pumps”. This contrasts with the common fragmented operational model were one group drills wells – often a government drilling section or a contractor – and a second group is responsible for the task of installing pumps. While this arrangement worked reasonably when district or provincial water engineers were solely responsible and financed the drilling and equipping of wells within a single financial year, it broke down when field work was disrupted, or a financial over-spend curtailed installation work. When this happened a number of recently completed wells were left with no pumps installed at the end of that financial year and there was usually no budgetary carryover to fund their completion in the next financial year. By the time funds became available to equip these suspended wells, the installation teams frequently could not find the well or the hole was partially or totally blocked with stones.

Across Africa, the number of uncompleted, but successfully tested wells is poorly recorded. Where data is available, the figure probably represents 20 to 30 percent of the total successful drilled-wells (Table B5-1) but can be considerably more. Of 243 boreholes drilled in 1971 by the Zambian Government, 60 were dry and abandoned, 118 were equipped and 125 were unequipped (DWA, 1974).

A 1987 inventory of wells in Ethiopia showed that, while the majority of the uncompleted boreholes were drilled after the end of a rural water supply programme of United Nations Children's Fund (UNICEF) in 1981, some of the successful UNICEF boreholes had stood unequipped for 12 years.

To add to this view of wasted endeavour can be added the large number of investigation boreholes drilled during Water Master Plan investigations and small town water supply feasibility studies across Africa and

Asia. In 1979-82, two water master plan studies in Tanzania drilled 53 and 70 boreholes with a 65 percent success rate but no hand-pumps were installed. In contrast, India Mk2 hand-pumps were installed by the drilling crew in eight of the 20 investigation holes constructed for a Battambang Urban Water Supply study, funded by the UK Department for International Development (DfID) in 1994.

Table B5-1: Status of Boreholes drilled between 1973 and 1989 in Ethiopia

Total Boreholes drilled	Equipped with motorised pump	Equipped with hand pump	Capped waiting pump installation	Abandoned
540	97	179	135	129

A number of reasons – such as the need to know type and size of pumps and installation depth – can be given to justify this break in what should be a continuous process of well construction, testing and pump installation. In many cases, these reasons are immaterial, particularly in the case of hand-pumps, and can be short-circuited by improved management and a flexible supply chain, as suggested in the 1960 UN publication. In fact, the only acceptable constraint may concern groundwater quality, but with a borehole database this should rarely arise.

A 1998 analysis prepared for the World Bank uses different terminology, with the 1978-1988 period being considered the appropriate technology phase and the 1988-1994 period as the transition from a hardware to a software phase (Black, 1998). Translated this implies recognition of the supply-side failure took ten years and that a further ten years were required to fully recognize that sustainable development depended not on a central government demand but on the demand at the community level.

The perceived need for an appropriate technology phase contrasts against the earlier pragmatic approaches outlined in Box 4 and with the Wagner and Lanoix (1959) guidelines for rural water supply[5].

3.9 Legacy of modern hand-pumps – Sustaining a rural water supply culture

In 1981, the World Bank, faced with a low success rate of completed and on-going projects, initiated the Rural Water Supply Hand-pumps Project aimed at identifying suitably reliable village-level operation and maintenance (VLOM) hand-pumps (Box 6). Carried out by the UK Consumers Association, the testing work largely focused on the robustness and mechanical efficiency of the pump heads designed to lift groundwater up to 60 m (World Bank, 1984).

By the mid-1980s, internal reviews of donor and lending agency rural water supply programmes began to highlight a series of sustainability problems that required a major re-think of their project approach. Among the main problems was despite intensive testing, most hand pumps installed did not meet the VLOM concept. While the high profile role of UNICEF in promoting local manufacture of variations of the India Mk2 and Mk3 hand-pumps in Africa[6] is well documented, the skill levels required for 100 percent successful installations were not always available (Harvey and Skinner, 2002).

3.10 The ascendency of electric submersible pumps

As problems with hand-pumps were emerging, progress in electric submersible borehole pumps had rapidly evolved from the late 1940s when the first 250 to 600 mm diameter pumps were developed for urban water supplies and mine dewatering. The focal design problem with the submersible pumps was creating a waterproof seal around the rotating motor shaft. Mercury-filled seals were used on the first motors but as technology advanced, closer-machined mechanical seals were developed, and finally oil-filled motors provided a robust solution to the sealing challenge. By 1960, manufacturers began to market a wide range of efficient small-

[5] Wagner and Lanoix (1959) also highlighted the superior practicality of chain pumps over regular hand-pumps in terms of performance and maintenance.

[6] UNICEF continues to fund some 20 percent of the 35 000 and 55 000 India Mk2 and Mk3 hand-pumps shipped annually to Africa between 2005 and 2009 (UNICEF, 2010).

diameter pumps. Commercial irrigation farmers, however, were hesitant to replace their known entities with untested pumps that required access to specialist repair facilities.

In the 1970s electric submersible pumps coupled with diesel generators were being increasingly used for rural water supply purposes in Africa and Asia with variable results. Exceptionally at Dubti in Ethiopia, in 1988 one such pumping set had been in daily use for over 14 years with the minimum maintenance and no overhaul (Jones, 1990). The normal lifespan for similar pumping sets was less than five years. From the mid-1970s, the expansion of rural electrification networks saw even greater use of submersible pumps (Box 7). Advances were also made with the introduction of precise, more robust and user-friendly, electronic-pump motor starter and protection switches to handle pump overloads.

Submersible pumps opened up the opportunity for solar powered photoelectric pumping with the first commercial sets being marketed in the early 1980s. Initially photovoltaic cells were expensive with a low efficiency at around 2 percent: this is has been improved to 9 percent. Matched with either DC or AC electric submersible pumps, solar power can produce up to 250 m^3/day against heads of 200 m. In areas with less dependable solar radiation, shaft driven positive-displacement, progressive cavity pumps are preferable to submersible turbine pumps as they will pump water work across a wider range of shaft rotation speeds.

Box 6: The Hand-pump Conundrum

During the late 1970s, the UNICEF rural water supply programme in India adopted, and helped with the development of the India Mk2 hand-pump (Mudgal, 1997). By 1980, a huge local demand for the hand-pumps and competition between manufactures brought the price of the India Mk2 with 50 m of rising main down to USD 200. It was also claimed that the pump satisfied VLOM status.

The low unit price and ready availability made the India Mk2 first choice for many of early IDWSSD projects outside India. However, removed from the mechanical support infrastructure available in India, the Mk2 pump proved difficult to install faultlessly and to subsequently maintain. There were inherent quality problems with the rising mains supplied and with other aspects of the India Mk2 pumps exported by some manufacturers, despite the controls and inspections developed between UNICEF and the Indian Standards Institute, initially, and later with the British Standards Institution and SGS – *Société Générale de Surveillance* (Jones, 1990, Baumann, 2000, Michael and Gray, 2005). However, the chain link connector between the pump arm quadrant and the pump rods is a constant cause of failure, particularly when the pumps are set at a shallow depth (Michael and Gray, 2005). Used in shallow wells, the weight of the rods is insufficient to push the plunger quickly down the cylinder as the handle is lifted: this causes the chain link to buckle. The situation is further aggravated by users developing a habit of using short quick strokes. The cost of mobilizing a technician to do the repair was many times the price of the spare part. When correctly installed deeper, the India Mk2 (>4 pump rods) can give over five years of heavy, trouble-free, performance as can the solid-link India Mk2 variant when the use of less than four pump rods is needed.

By the late 1970s, internal reviews of donor and lending-agency rural water supply programmes found that the repair of broken down hand-pumps was beyond the capabilities of most rural communities. The main problem was that despite intensive promotion, the hand-pumps did not meet the VLOM concept. In 1981, the World Bank frustrated by this low sustainability of completed and on-going projects, initiated the Rural Water Supply Handpumps Project aimed at identifying suitably reliable pumps. Many had inherent design weaknesses like the use of plastic crown wheel and retaining set screws that worked loose under use in some versions of the Mono progressive cavity pump (Jones, 1990). The rotor was also liable to become jammed in the stator if silt collected in the pump. The results of the tests and subsequent Water Aid analysis (Water Aid, 2007) are shown on Table B6-1.

Table B6-1: Selected hand-pump performance and VLOM characteristics (from Water Aid, 2007).

Name	Type	Lift Range m.			Discharge l/min			VLOM	Origin
Afridev	Deep well	7	25	45		22	15	Yes	Kenya, etc.
Afridev	Direct action	7	15		26	22		Yes	Kenya, etc.
Bucket pump	Improved bucket and rope	6	15		5	10		Yes	Zimbabwe
Consallen	Deep well	7	25	45	14	14	14		UK
India MK 2	Deep well	7	25	14	12	12	12	No	India, etc.
India MK 3	Deep well	7	25	45	50% of Mk2				India, etc.
Monolift	Deep well progressing cavity	25	45	60	16	16	9	No	UK, South Africa
Nira AF 76	Deep well	7	25		25	26		No	Finland
Nira AF 84	Deep well	7	25	45	23	22	21	No	Finland
Nira AF 85	Direct action	7	15		26	24		Yes	Finland
New No. 6	Suction pump	7			36				Bangladesh
Tara	Direct action	7	15		24	23		Yes	Bangladesh
Vergnet	Deep well diaphragm	7	45		24	25		No	France
…	Windlass and Bucket	0	45		5	15			Universal

Promoters' annual reports of IDWSSD hand-pump projects, however, were quick to announce their success clusters along the lines of: *in the past year our projects provided safe drinking water to so many hundreds of thousand people*. To which, many field workers could reply: *yes, but for how long?* Figure B6-1 provides a partial reply. It shows the situation with broken down hand-pumps across a number of sub-Saharan countries.

The results from elsewhere are likely to mirror these results: McJwikin (1977), for example, highlights the weaknesses of many of the commercially manufactured hand-pumps then available.

Looking at the mechanical reasons for the breakdowns (Figure B6-2) recorded by Reynolds (1992) shows a close correlation with the earlier experience in the operation and maintenance of rural hand pumps. In the 1960s and 1970s, most problems affected, in order of frequency, plunger washers, foot valves and pump cylinders. The pump heads were then largely of the heavy-cast iron lever or rotary type.

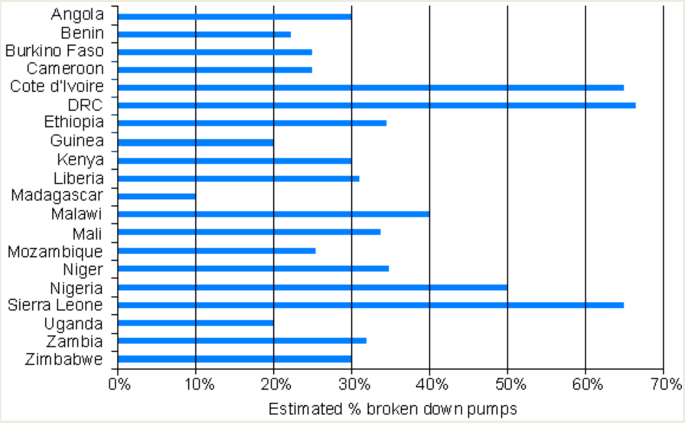
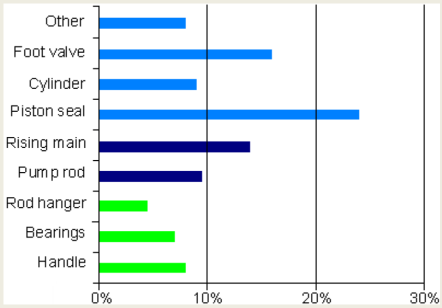


Figure B6-1: Percentage of broken down hand-pumps in selected Sub-Saharan countries (from RWSN, 2010).



Light blue - down-hole components
Dark blue – rising main components
Green – headwork components

Figure B6-2: Main causes of hand-pump breakdowns (from Reynolds, 1992).

The high frequency of down-hole component failures suggests two possible causes. The pump seals and cylinders may have reached the end of their service life or they are prematurely worn out due to the inflow of abrasive silt or sand into the pump body. This inflow would also account for jamming of the foot valve. The use of manmade materials rather than traditional leather for the pump seal or cup has not proved entirely satisfactory in terms of working life or efficiency. The self-healing nature of wet leather allows stray sand grains to embed into the seal rather than to be trapped on the surface where it can abrade the cylinder walls. The use of a short cylinder length as a cost-cutting measure has downside impacts. It makes the alignment of the piston stoke within cylinder very critical and removes the opportunity of relocating the piston movement to an unworn part of the cylinder: this is frequently done by turning the cylinder upside down.

The difficulties of replacing the down-hole components was recognized and addressed with a number of pumps having foot valves and pump plungers retrievable without removing the whole pump and rising main. This is a feature of the Afridev pump that can also be supplied with unplasticized polyvinyl chloride (uPVC) plastic rising main.

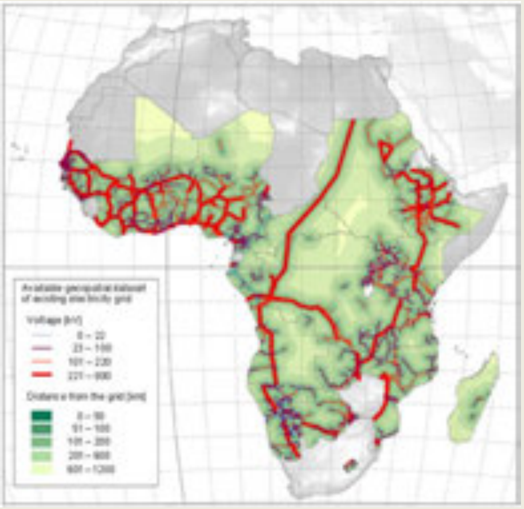
The problems with the rising main and rods can usually be traced to poor assembly during installation or poor quality materials: corrosion of badly galvanized pipes and fittings is a particularly problem. The lower percentage of breakdowns associate with the pump head suggests that accessible components are more readily repaired (Mbamali, 1998).

The criteria for judging hand-pumps performance used by the World Health Organization (WHO)/UNICEF Joint Monitoring Programme – JMP (WHO/UNICEF-JMP, 2000) classifies a pump as functioning if it works for more than 70 percent of the time and it is repaired within two weeks of breaking down. Even within these generous criteria, the JMP reports that only 70percent of rural water supply systems were functioning between 1990 and 2000 in Africa and 83 percent in Asia.

Irrespective of the cause of hand-pump failures, they result in endless inconvenience and added health risks to the rural communities unless a workable maintenance solution is in place. The lack of this interface lay behind the poor performance of many early IDWSSD hand-pump projects and exposed the inherent weakness of the supply-side driven projects.

Box 7: Rural Electrification – Opportunities Missed and Open

In 1988, 132 kV electric power lines, commissioned in the mid 1980s to supply the Kombolcha Textile Mill and Dese, follow 150 km of the Ethiopian Highway E1 between Shewa Robit and Dese. They passed over a string of local rural market towns and administrative centres with populations of several thousands but, with substations widely spaced, 33 kV supplies reached very few communities. This limited the number of communities that could benefit from mains electrification under the DfID Welo Well Rehabilitation Project and appeared a missed opportunity.



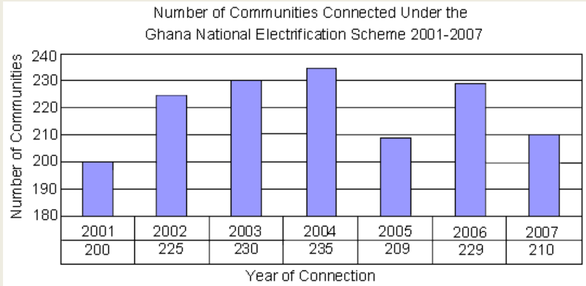


Table B7-1 (above): Progress 2001-2007 on rural electrification – Ghana. (Adapted from Abavana, 2008)

Figure B7-1 (left): Rural electrification distribution in sub Sahel Africa (from Szab´o et al., 2011)

The design of a European Union (EU) water supply and sanitation project implemented in 40 small towns in Ghana specifically aimed to take advantage of the first phase of the rural electrification programme in the Central and Western Regions. The project followed the Western consultancy pattern with pre-feasibility, feasibility and implementation phases tailored to conform to the client's practical design, operation and maintenance guidelines. The project ran from 2000 to 2012. Preparation took 24 months, prefeasibility study and feasibility studies required 33 months and implementation lasted 54 months. The total cost was ca. 17 M Euro. The extended implementation period led to community discontent: the communities had to raise 5 percent of construction costs up-front to qualify for inclusion in scheme. This was demanded during the feasibility phase and handled by community water committees who were embarrassed by the 4 or 5 years of inaction between revenue collection and the arrival of the construction consultants and contractors.

This type of development is questioned by Vaa (1993) who believes such projects should follow the 1970's World Bank Technology Advisory Group model, based on the recommendations of Sounders and Warford (1976). This model initially only aims at substantive improvement of existing supplies as opposed to fully-fledged and engineered schemes. In the EU project, each town had several existing boreholes constructed under a 1988-89 German-aid project that constructed 3 000 boreholes fitted with VLOM hand-pumps. In several cases these wells were suitable for equipping with an appropriate submersible pump for the planned urban piped-water supply but, if a lesser level of service had been agreed for the EU project, many of the frequently broke hand-pumps could have been replaced with single phase 98-mm-diameter electric submersible pumps producing 2 to 6 m^3/hour and feeding to a small storage container. As the pumping head is unlikely to exceed 50 m, the power consumption of 0.37 to 0.75 kW motors is low. A maintenance-free pump operating life in excess of five years plus the small diameter rising main (optimal 40 mm), are usable power cable and the possibility of using a pre-pay electricity metering (potentially including a built-in supplementary charge to cover future maintenance and replacement costs) negate many of the operational problems encountered at community level. Other advantages include rapid, low up-front, implementation costs, relatively simple technology involved with the starter switch and very little delay between community consultation and pump installation. The technology also allows the communities to consider solar and wind power alternatives and to install their own water distribution pipelines if inclined. Finally, with appropriate monitoring of the pumps and community management will provide concrete feasibility data for subsequent expansion to a full pipe supply.

The past and planned expansion of rural electrification in Ghana (Table B7-1), coupled with the newly completed comprehensive groundwater inventories for many regions and a manageable level of funding, should allow a rapid replacement of the difficult to maintain, broken hand-pumps with submersible pump installations as an intermediate step towards the implementation of fully engineered piped-water supplies. It also preserves the value of the past borehole drilling programmes. The simplicity of the scheme places it within the capabilities of community water management committees and certainly within the scope of the local supply chain. The adoption of similar pumps for rural irrigation in India shows the practicality of the model. Figure B7-1 shows the scope for similar schemes to follow on the heels of all rural electrification programmes across Africa and elsewhere.

3.11 Diesel powered shaft-driven pumps – A dying culture

With obvious efficiency and installation advantages over shaft driven pumps, by the mid-1980s electric submersible pumps were replacing line-shaft pumps for urban water supplies. At the end of the 20th century, covering a very wide range of yields and heads, submersible pumps had achieved market dominance. Relatively inexpensive, easy to install and with a maintenance-free life-span of 10+ years, the use was further advanced by the spread of rural electrification.

The 1980s saw the economic assessment of groundwater production shift to whole-life costing (Hydraulic Institute, Europump and US Department of Energy, 2000). This shows the energy costs to far outstrip the capital cost of the borehole pumps. Electric submersible pumps benefit from being virtually maintenance-free compared to direct-drive diesel or liquid petroleum (LP) gas engines that require regular servicing and have a shorter working life. The 1980s, therefore, saw a rapid worldwide take-up of submersible pumps for groundwater irrigation. Coupled with centre pivots large-scale farmers were able to improve crop yields on all continents. In Nebraska, between 1972 and 1986, the number of centre-pivots in use rose from 2 700 irrigating 151 200 ha to 26 208 irrigating 1 360 000 ha (Kepfield, 1993). In Libya, submersible pumps were central to the development of the groundwater resources of Nubian Aquifer System that had been identified in the 1960s. To a large part, submersible pumps coupled with rural electrification considerably added to the productivity of India's 1970s Green Revolution.

At the close of the 20th century in India, China and the USA, the number of irrigation wells in use continued to rise. Table 2 provides a snapshot of the expansion and transitions in the irrigation pattern and costs in Nebraska. The growth in diesel-powered pumps indicates the continuing use of line-shaft pumps as new land is opened up for irrigation in response to an increase in agricultural price subsidies and a push to soya- and maize-based biodiesel production.

Table 2: Nebraska groundwater irrigation statistics and sources of energy abstracted from the US Census of Agriculture, Farm and Irrigation Surveys of 1998 and 2003

Year	Number of Pumps	Electricity		Diesel		Gasoline		Natural gas		LP Gas	
		Cost / ha	ha irrigated	Cost / ha	ha irrigated	Cost / ha	ha irrigated	Cost / ha	ha irrigated	Cost / ha	ha irrigated
1998	47 643	55,00	841 250	45,20	54 497	27,55	3 454	48,7	390 805	39,33	3 400
2003	69 583	70,00	1 168 830	74,23	920 974	113,63	551	97	483 058	73,93	214 924

3.12 Power supply and the electro-submersible

In India, subsidies were directed at farm inputs, mainly fertilizer and electricity. From the early 1980s, this resulted in an expansion in groundwater irrigation into areas previously limited to rain-fed or small-scale surface-water irrigation farming. Initially, electric-powered centrifugal suction pumps installed in hand-dug wells were sufficient to supply irrigation water for most farms. By the mid-1980s, farmers responded to declining groundwater levels by drilling boreholes in the bottom of hand-dug wells and setting the pumps lower in the well. As in the USA, further declining groundwater levels required a shift to shaft-driven or submersible pumps and the farmers in India were faced with the increasing costs of new equipment, higher lifting heads and longer pumping hours per day. By the late 1990s, the serious doubts voiced by the groundwater specialists about the sustainability of the groundwater abstraction were largely diverted by local politicians who relied on the goodwill of their farming electorate.

In the neighbouring countries of Bangladesh and Sri Lanka, farmers were encouraged to take up groundwater irrigation by subsidised diesel-pump purchase schemes.

Estimates by the end of the 20th century suggest as much as 20 percent of energy worldwide was used by pumps of various types (Hydraulic Institute, Europump and US Department of Energy, 2004). This high energy use brought into focus the need to improve the efficiency of both the pumps and pump motors. While there is no breakdown of what percentage was used to pump groundwater, it is possible that it was 1 or 2 percent, and almost certain that at least 75 percent of this usage was for pumping groundwater for irrigation. The remaining being split between urban and rural water supplies, land drainage, mine and construction works de-watering and a small percentage for air conditioning and heating.

3.13 Low head suction pumps – Low intensity scavenging of shallow groundwater

By 2000, various pumping technologies had been developed to skim either good quality groundwater from the top of saline groundwater bodies or hydrocarbon or other pollutants from contaminated aquifers. The skimming technology has close affinities to construction industry dewatering requirements that involve controlled lowering of groundwater levels. However, limited use is made outside the small island context of well points and suction pumps to abstract groundwater from the shoestring river alluvial tracts for piped domestic water supplies (Svubure *et al.*, 2011). In the 1970s, well points were used relatively extensively along the Zambezi floodplain in Western Province of Zambia, and the town of Mongu in Zambia was provided with such a system. To quote the 1974 Annual Report of the Zambian Department of Water Affairs (DWA):

> Under the co-operative and village water supplies programme well-point sinking and the installation of Uganda hand-pumps continued and in all 135 well-points were completed successfully, 24 more than in the previous year. There were fewer abandoned well-points as it was possible to use the small percussion rig to drill deep enough to reach the water table where the jetting method had failed. However, this is slower than jetting and expensive on labour.

Most groundwater decontamination systems depended on the steady low-yield continuous-abstraction pump characteristics of gear, peristaltic and bladder pumps. Compressed-air-powered pumps are commonly used for hydrocarbon recovery but continuous porous fibre belt recovery pumps that soak up pollutants mirror the long established rural water supply rope pump mechanism.

4. Technology Baseline and Associated Cultures of Use in the 21stCentury

4.1 Regulation and consolidation of pump manufacture

Established in 1960 by European pump manufacturers, the Europump Association now monitors industry compliance with the EU directives covering machinery efficiency that have been issued since 1989. The expansion in globalization and consolidation of the international pump industry during the first decade of the 21st century has seen Europump work in partnership with other manufacturing organizations including notably the United States Hydraulic Institute. Evolving improvements cover hydraulic design, motors and computerized controls aimed at improving efficiency. In many parts of the world, a range of constraints forces users to rely on the cheapest available pumps that tend to be inefficient and have a short working life. Huang, Rozelle and Hu (2007) describe the growth in response to a worldwide demand of an irrigation-pump manufacturing cluster in Daxi, China.

The 21st century sees emphasis placed on the sustainability for all forms of development coupled to rising concerns with resource management and climate change. The push to develop integrated water resources management plans has to be seen against the limited information on the resource base and current lack of understanding of the hydrological processes in many parts of the world.

4.2 Improved pumps and groundwater over-development, inevitable self-perpetuating trends?

The potential for expanding agricultural production is being explored against a background of almost universal groundwater level decline in existing areas of groundwater irrigation. In some developments, this has been planned for – e.g. the exploitation of the Nubian Sandstone in Libya – but in most, there has been no pre-planning and the impact of over abstraction has had major social and economic consequences. This problem becomes more pressing where uncontrolled groundwater abstraction encroaches on urban water supplies as seen in Sana'a, Yemen (Charalambous, 1982; World Bank Group, 2010).

The International Water Management Institute (IWMI, 2007a) classification of groundwater irrigation economies identifies the main indicators and economic attributes to the developments, but it does not provide a guide to the management of the resource. In addition, traditional pastoralists' livestock-watering needs have always been closer to rural domestic water supply than irrigation unless there is a heavy dependency on irrigated fodder production.

Across Peninsular India and elsewhere in Southeast Asia, the green-revolution-based groundwater irrigation, has received, and continues to receive, a high national priority. The virtually unrestrained groundwater abstraction has emerged as unsustainable in resource terms in many of the main groundwater irrigation areas (Figure 2). Seeking to control the groundwater irrigation abstraction has to recognize that the farmers' choice of crops, irrigation practices and need for water are strongly orientated by subsidies and tax breaks.

4.3 The US High Plains Aquifer wilful over-exploitation

Since 2000, groundwater abstraction from the US High Plains Aquifer has continued to grow and groundwater levels continue to decline (Figure 3) under a regime of strong, technically-based and enforced groundwater rights legislation that, in most States, embraces controlled over-abstraction as an accepted policy. The highly motivated commercial farmers ensure high pump efficiencies and use diesel-powered line-shaft turbines to open up new areas for groundwater irrigation.

As the farmers in the Northern High Plains States continue to optimize the quantity of water available for irrigation, the municipal water supply companies are acutely concerned with the water quality. The impact of agricultural activities on both surface and groundwater quality has steadily increased since homestead farming became agribusiness. The consequences of further expansion in biofuel feedstock production may well undo any of the other environmental benefits achieved. Greater use of limited and deficit irrigation practices could lead to economies in water usage and enable an expansion in the irrigated area, but the impact of the additional agro-chemicals needed, will stretch in to the future. How much damage to the environment will take place before the "cleanest production pathways" and the lowest production carbon footprint are achieved remains to be seen (Roberts, Male and Toombs, 2007).

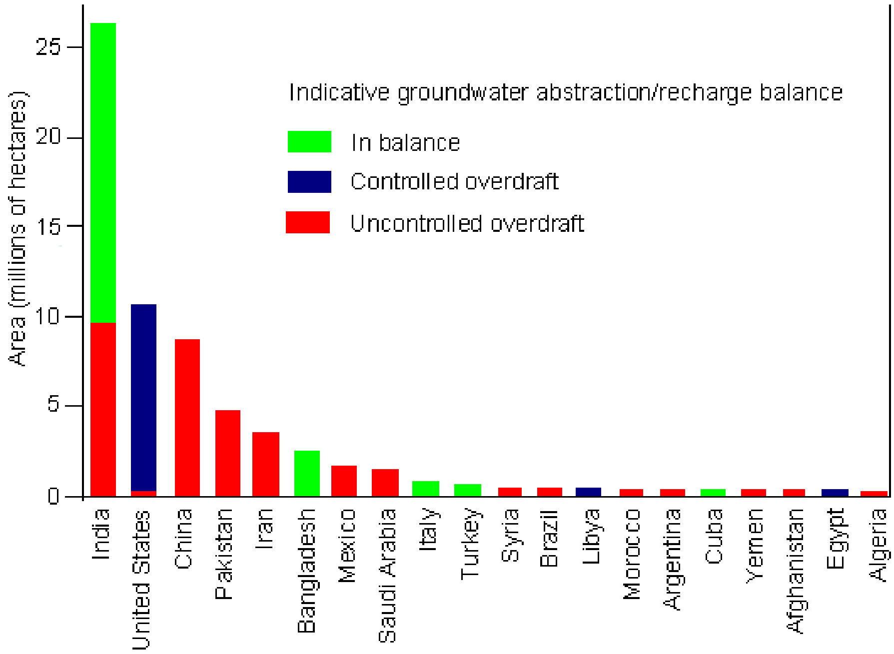


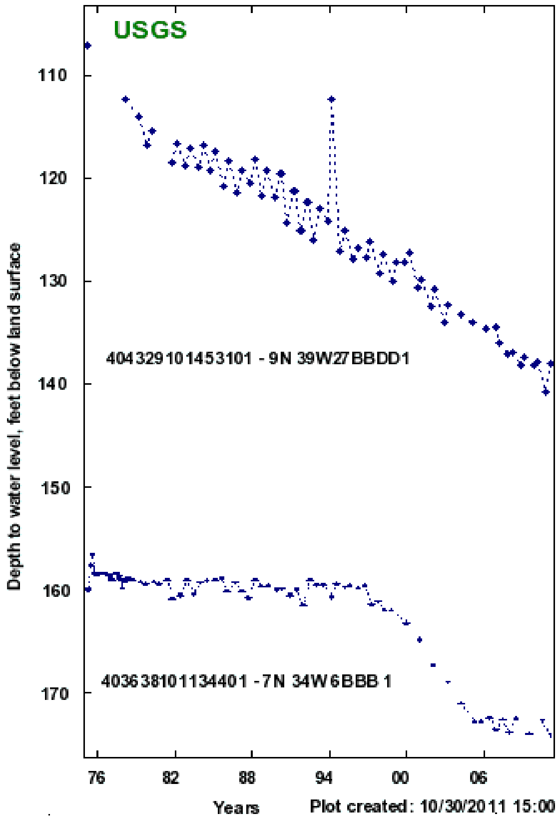
Figure 2: Area under groundwater irrigation by country: 1993-2002 with subjective view of irrigation withdrawal-recharge balance. Areas exploited under the rule of capture considered as being effectively uncontrolled developments (based on IWMI, 2007a and FAO Aquastat, 2005 data).

The situation under the rule-of-capture water rights legislation in the Texan High Plains has seen some groundwater irrigation areas retired due to uneconomic pumping costs or deteriorating water quality. The Texan Groundwater Conservation Districts (GCDs) main approach to resource conservation applies some form of depletion formula based on retaining a percentage (usually 50 percent) of the existing groundwater in storage at a certain date in the future (typically 2050). In 2002, following legal and technical processes, the Mesa Water Group obtained permits in 2002 to sell 39.5 Mm^3/year of groundwater to metropolitan areas in Texas under the established (Texas) Panhandle Groundwater Conservation District regulations (Freese and Nichols, Inc., 2006). The conditions of the permit were as follows:

1. Pumping must be limited to one-acre foot per year per surface acre (3 005m^3/year).
2. Fifty percent of the 1998 aquifer volume must remain in place in 2048 ("50% Rule").
3. Water may be sold only for municipal use within Texas.
4. Wells must be spaced and located to minimize impact on neighbours.

This represents the current limit to the control of groundwater pumping in the State of Texas and, to a large extent, worldwide where the rule of capture applies in lieu of other legislation in force.

The depth of scientific study involved in the quantification of the large-scale groundwater abstraction in the USA is huge, but the ultimate verification of the success of management plans depends on a well-funded and assiduous long-term monitoring programme. Whatever impact on-going biofuel feedstock production may have on the surface and groundwater resources, the US Geological Survey's National Water-Quality Assessment Program (USGS – NAWQA, 2007) and the local Groundwater Management Districts (GMDs) will be engaged in monitoring quantity and quality parameters. The speed at which groundwater levels decline or recover across the High Plains will show if the GMDs depletion assessments and rules are appropriate. It seems certain that farmers will maximize their abstraction rights and irrigation efficiency. It also seems certain that diffuse contamination levels in surface water and groundwater bodies will continue to spread while many of the known-point contamination sources and plumes will be contained and cleaned up.



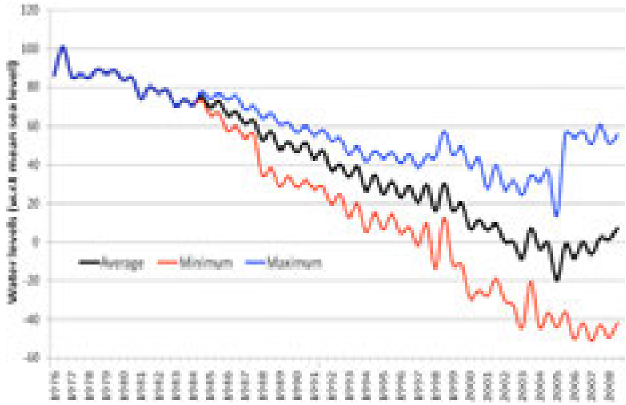


Figure 3: Groundwater Hydrographs from the High Plains Aquifer in Nebraska (left scale in feet) and Gujarat (above scale in metres) from 1976 to 2008 showing the impact of over-abstraction on groundwater levels.

The lower Nebraskan example shows the rapid impact as new areas are brought under groundwater irrigation. Nebraska graphs from USGS: http://groundwaterwatch.usgs.gov/StateMaps/NE.htm and Gujarat graph from: http://water.columbia.edu/?id=India&navid=Gujarat

To achieve future equitable groundwater management, the existing water legislation in the eight High Plains States will continue to evolve. The options available, however, are limited and will be met with objections from special interest groups and politicians. The general consensus is that groundwater levels and baseflow will continue to decline even if substantial cuts are made to groundwater irrigation (US Bureau of Reclamation, 2007). The substantive options available are:

- retirement of surface water irrigated lands;
- retirement of groundwater irrigated lands;
- retirement of groundwater irrigated lands with lagged depletions;
- introduction of interruptible water diversion rights.

All these options will involve some form of monetary compensation for surrendered water rights.

Finally, although the High Plains Aquifer provides valuable technical, legal and economic water resource development and management models that could be applied elsewhere, the regional population density has remained very low at 3.5 per km^2 since 1960. Also the differences in the climatic setting and hydrogeology must be taken into account. The Nubian Sandstone Aquifer of North Africa and large outwash tracts in Central Asia and South America are among the few potentially comparable groundwater occurrences.

4.4 Power supply and the electro-submersible – Progressive 'privatization' of supply

4.4.1 Sustainable or unsustainable, uncontrolled groundwater development in Southeast Asia

In 1960, around 100 000 centrifugal suction and low lift pumps were used for groundwater irrigation in India. With virtually no legal restrictions on groundwater abstraction, by 2000 the number of pumps had risen to over 19 million, and by 2007 over 25 million pumps were in use. The associated growth in groundwater abstraction, irrigation area and electricity usage (Box 8) has been instrumental for the steady decline in groundwater levels shown on Figure 3. No distinction is made between electric pump types in published references: many in the major river basins are either suction centrifugal or shaft-driven turbine pumps. The number of electric submersible pumps is not recorded but their widespread use since 1980 is largely responsible for the decline in groundwater levels in many Indian Peninsular States.

Box 8: Groundwater Irrigation in India

Countrywide in 2007, 25 percent of the farmers in India had tube wells, and an additional 50 percent bulk purchased groundwater for irrigation (Shah, 2007a). Fifty-seven percent of the pumps in use were electrically powered and 43 percent were diesel-powered. Figure B8-1 shows the distribution of these pumps in relation to the motive power. This distribution reflects past phased changes in the rural electrification network:

- Phase I:1935-1965, struggle for demand creation;
- Phase II: 1965-1975, early expansion in electric tube wells;
- Phase III: 1975-2004, take-off in GW irrigation under flat tariff;
- Phase IV: 1985-1998, de-electrification of rural eastern India;
- Phase V: 2002-to date, reversal under energy demand reduction scheme.

In areas with robust rural electric supplies, groundwater pumping accounts for around 40 percent of the energy consumed. In areas with low or poor electrical supplies the pumping accounted for around 10 percent in 1998 (CMIE, 2003). To maintain agricultural production, subsidized diesel-pump purchase was provided in the areas under the de-electrification phase. The rise in pump numbers led to increases in the area under irrigation (Figure B8-3), groundwater abstraction (Figure B8-2) and electricity usage.

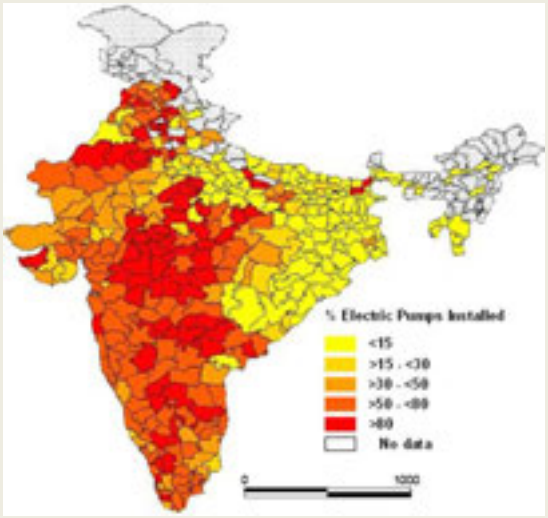


Figure B8-1: Percentage distribution of electric pumps in India (from Shah, Giordano and Mukherji, 2012).

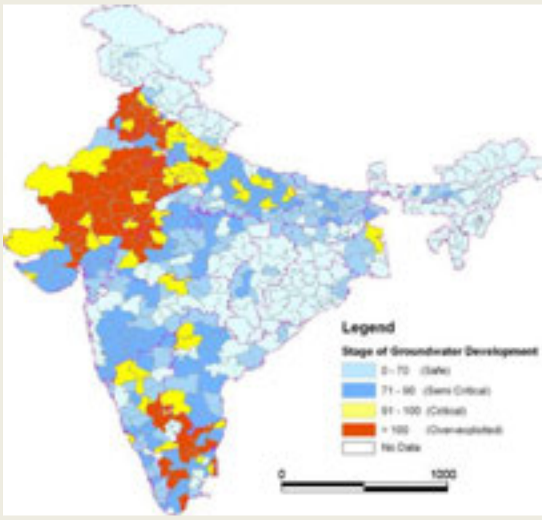
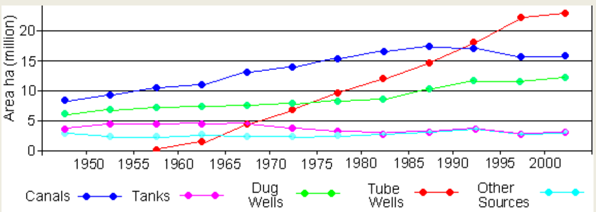


Figure B8-2: Groundwater development levels (from CGWB-MoWR (GoI), 2006).

Cuts to the rising cost of continuing the input subsidies inherent to the green revolution have to be balanced against the need to maintain social stability in the rural areas. In 2011, subsidies covering the irrigation and electricity costs reached 75 to 90 percent of the wholesale market value (Figure B8-4). Reducing the Government cost of subsidizing maintenance and expansion of groundwater irrigation is being addressed by a variety of initiatives carried out at both the State and Central level. The necessary adjustments, however, face strong local community and political resistance.



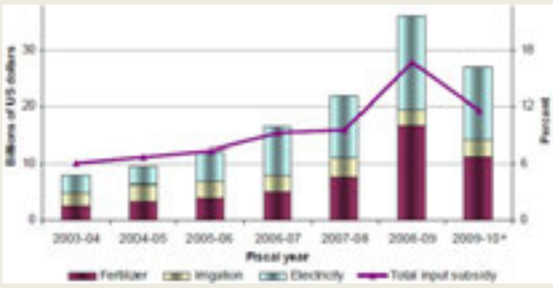


Figure B8-3: India area under irrigation and water sources (Government of India, 2003).	*Figure B8-4: India Agricultural Input subsidies in USD and percentage of agricultural output value (Grossman and Carlson, 2011).*

Beyond the impact of the Indian pump subsidies on groundwater levels, is the question of over-irrigation. Although statistics for the area under groundwater irrigation are readily available, similar abstraction data is elusive: the Central Groundwater Board of India (CGWB), however, quotes countrywide totals of 115 km^3 in 1995 and 231 km^3 in 2004 (of which 213 km^3 is assigned to irrigation use). These equate to an annual irrigation application of 398 mm in 1995 and 564 mm in 2004.

Hidden behind these statistics are problematic facts facing the irrigators and the Indian Central and State Governments:

- Access to pumps and energy supplies;
- The wide range of farm sizes and social standing of the farmers;
- The reliability of the electricity supply;
- The energy efficiency levels of the pumps, motors and ancillary pipe work;
- The role of subsidies in the agricultural sector;
- The extension of groundwater irrigation into the crystalline Basement and extrusive igneous rock areas of the Peninsula.

4.4.2 Access to pumps and energy supplies

In rural India, the early, bottom-up demand created by individual investment in wells and pumps for groundwater irrigation was invigorated under the impetus of the "Green Revolution". This led to a rapid rise in widely disperse rural agricultural energy consumption that overloaded the low tension (LT) distribution network capacity. This imbalance was entrenched by the introduction of flat rate electricity tariffs to lessen cost of metering that accounted for some 40% of the generating boards' outgoings (Shah, Giordano and Mukherji, 2012).

Starved of investment, the generation boards in the eastern Indian States found upkeep of the LT distribution impossible and much of the system was abandoned leading to the 1985-98 rural de-electrification (Box 8).

After this rural de-electrification in the high rainfall eastern States of India diesel-pump-based irrigation became dominant (Box 8). Subsidies aimed at the poorest farming communities for well drilling and irrigation pump purchases were introduced (Shah, 2001). When implemented, the subsidy schemes in some participating eastern States were initially hampered by bureaucratic inefficiencies, and the poorer farmers preferred to purchase their own diesel pumps. After reviewing the scheme, the states adopted a system where the pump dealers became the lynchpin of the operation, handling the paperwork and organizing the drilling contractors.

Later commercial banks became involved and arranged loans to the farmers with 3 to 5 year repayment terms. The success of the scheme can be seen in the prevalence of diesel pumps shown on Figure B8-1. In West Bengal for example, the ratio of diesel to electric pumps is 9 to 1. Almost all the new electric pumps installed since 1991 belong to the wealthier landowners who could afford the high connection costs and consumption tariffs charged by the Generating Boards (Figure 4). They also frequently profit by selling irrigation water to the poorer local smaller landowners (Figure 5).

Faced with diesel price rises, many less affluent farmers in Assam are effectively withdrawing from irrigation and selling their irrigation pumps to newly-formed, minority, start-up farming groups. Growing social and political recognition of the need to redress the disparity between subsidized electricity and diesel costs will inevitably lead to further rethinking of the various State subsidy practices. Irrigators in eastern India are pressing for a diesel ration or a subsidized price regime.

The results from the 1998 National Sample Survey Organization (NSSO) show the groundwater availability and electricity supply across Western and Peninsular India under significant pressure (Figure 6). The negative view of the supply situation appears to be largely unconnected to the unit cost of the agricultural electricity supply. The subsidized electricity prices below around 30 paise/kWh (ca. USD 0.007 at 2012 rates) are clearly the main reason for a wastage of resources (Shah, Giordano and Mukherji, 2012 who quote an average generating board basic unit production and delivery costs of USD 0.04).

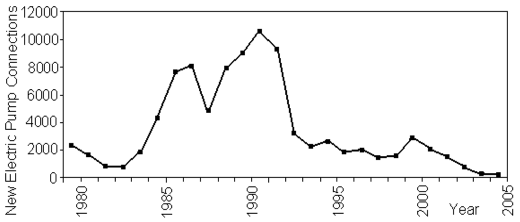


Figure 4: East Bengal new electric pump connections 1979 – 2004 (adapted from Mukherji, 2007).

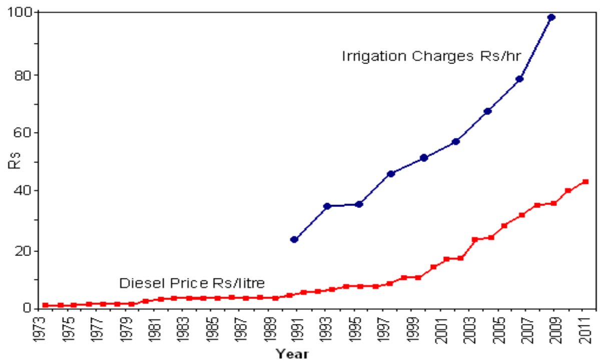


Figure 5: Uttar Pradesh diesel and irrigation water price rises (adapted from Shah, 2007b).

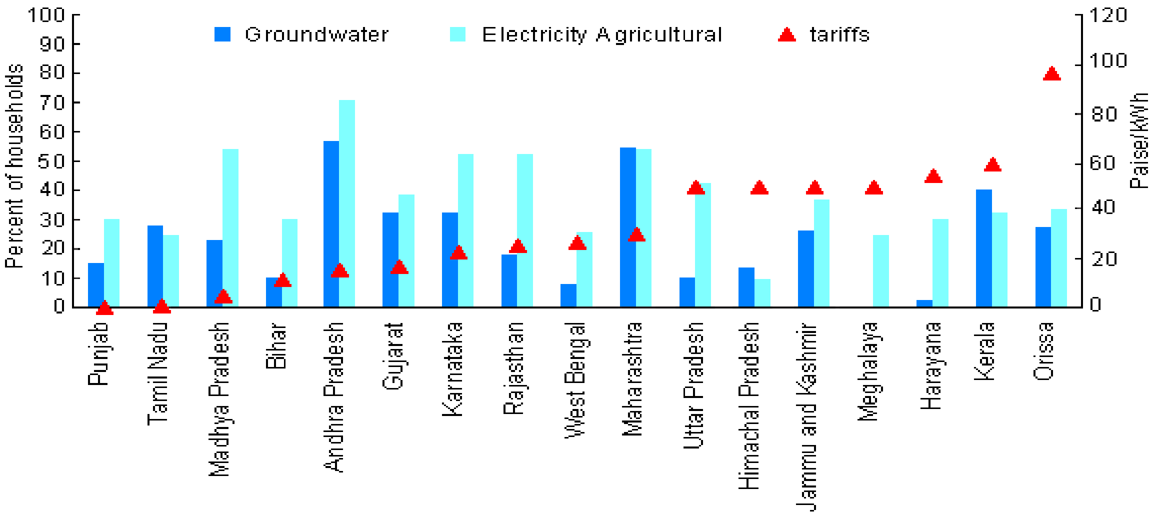


Figure 6: Farmers reporting inadequate access to groundwater and electricity in 1998. The Indian States are ranked by their agricultural electricity tariff (redrawn from Birner, Surupa and Neeru Sharma, 2011).

4.4.3 Wide range of farm sizes and social standing of the farmers

Figure 7 is based on the 2003-2004 NSSO land and livestock data and shows that these farming groups in Gujarat, Maharashtra, Andhra Pradesh and Karnataka represent more than 70 percent of the farming households and that they own less than 15 percent of the land. The figures for the marginal farmers are considerably worse: they represent around 50 percent of the households and own less than 5 percent of the land. Their access to groundwater is largely dictated by the geomorphological setting of the individual farms. Those close to the water divide and along the upper interfluves should receive reasonable seasonal recharge and support low yielding hand dug wells and shallow boreholes. Lands with better developed and thicker weathered regolith aquifers across the lower interfluves and on the valley floors are likely to be the target for competitive groundwater abstraction by the owners of larger farms. Marginal and small farmers with limited land in these settings are unlikely to afford the deeper boreholes and the higher cost of pumping, unless they associate with neighbouring farmers to equitably share the available resource.

The land ownership pattern and size of farms in the Ganges Basin States is shown on Figure 8. As seen across Peninsular India, the land redistribution programmes in West Bengal, Jharkhand and Bihar, and to a lesser extent in Uttar Pradesh, have benefitted the marginal, small and medium farm holdings. This contrasts with the position in Punjab and Haryana where less than 10 percent of the medium- and large-scale farmers control over 50 percent of the land.

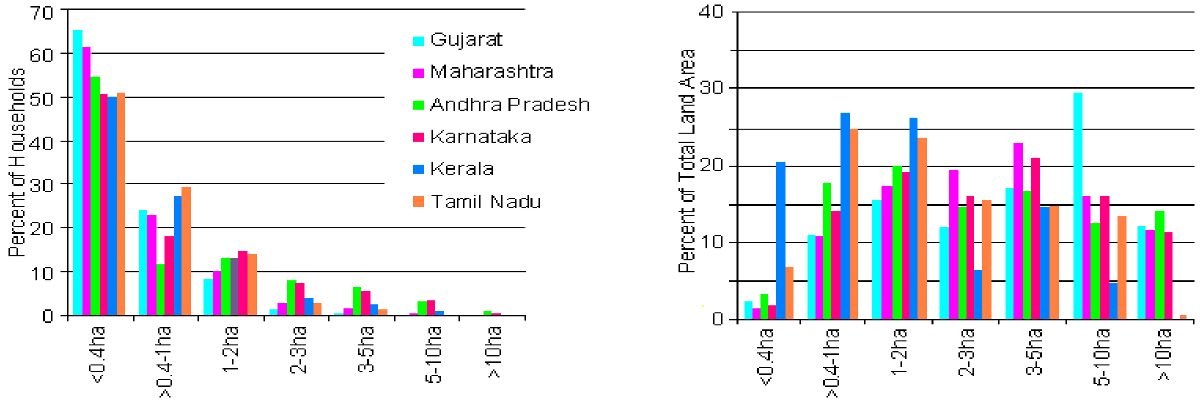


Figure 7: Peninsular Indian States – percentage distribution family farm sizes and percentage areas owned by marginal farmers (>0.4 ha), small farmers (0.4-1 ha), medium farmers (2-5 ha) and large farmers (>5 ha) (data from Rawal, 2008). The marked difference between the Kerala and Tamil Nadu family holdings reflects the State post-colonial land redistribution and the effect of the land-holding size cap.

The rural de-electrification of the eastern states of the Ganges Basin and the introduction of subsidized diesel pumps and tube-well programmes coupled with favourable hydrogeological conditions has been covered by Shah (2001 and 2007b) and Mukherji (2007). The shared consensus is that groundwater irrigation remains viable without excessive electricity subsidies. Although these analyses accept a role for a groundwater market, experience from Punjab suggests this could be socially and politically unacceptable in the long run as indicated by Sarkar (2011) who states:

> The consequences of negative groundwater draft have mostly been viewed as an ecological disaster, but the externalities of groundwater depletion pose greater concern for socio-economic equity in the access to this resource. This empirical analysis signifies the concerns for the livelihoods of farmers, when the cost of depletion is disproportionately borne by the resource-poor farmers as they are unable to invest in capital and technology and are hence denied the benefits of groundwater irrigation that is subsidised by free electricity. This situation is perpetuated with further scarcity leading to unequal economic returns and, finally, takes the most exploitative form where the "large landlords" also emerge as "water lords" through surplus accumulation, forcing the small and marginal landholders to become landless agricultural labourers.

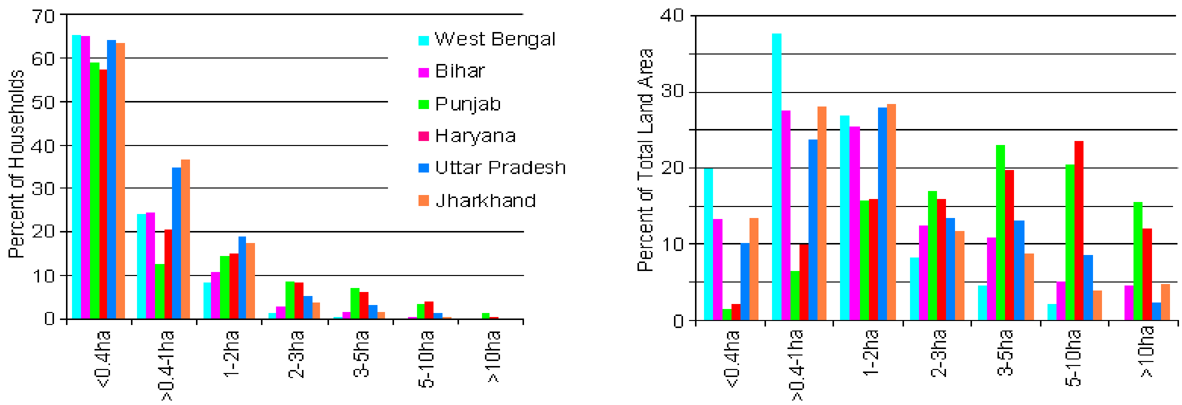


Figure 8: Indian Ganges Basin States – percentage distribution family farm sizes and percentage areas owned by marginal farmers (>0.4 ha), small farmers (0.4-1 ha), medium farmers (2-5 ha) and large farmers (>5 ha) (data from Rawal, 2008).

Table 3 presents the basis for this bleak but substantiated view of the situation in the Punjab State. The data is from three villages within the alluvial floodplain of the Ganges River system where the depth to groundwater ranges from 12 m below ground level (bgl) at Tohl Kalan to 18 m bgl at Gharinda and 46 m bgl at Ballab-e-Darya. It is considered that this analysis may well prove as valid as that for the domestic water supplies in East Africa as described by White, Bradley and White (1972).

Sarkar (2011) concludes that landowners without their own secure source of irrigation water are considerably disadvantaged. He observes that landowners or farmers leasing in land, and who are dependent of the local water market, have consistently lower crop yields than the self-sufficient landowners. This is considered to undermine the arguments that water markets work well and are largely self-regulating. As already indicated, water buyers are unlikely to have security of supply or guarantee to an equitable price (Figure 5). Singh (2007) identifies a similar potential insecurity attached to the water market available to the marginal landholders in Rajasthan.

Table 3: Subjective assessment of basic technical and economic factors influencing groundwater irrigation farming in three village communities in Punjab, India (data from Sarkar, 2011).

	Marginal farmer	**Small farmer**	**Medium farmer**	**Large farmer**
Mixed irrigation village (Tohl Kalan)				
Number of farmers	18	26	38	18
Average number of operational tube wells (%)	0,72	0,96	1	1
Average depth of tube well (m)	45	58	70	98
Water purchased (no.)	4	5	9	2
Water sold (no.)	2	7	6	6
Land leased out (no.)	11	23	13	50
Land leased in (no.)	6	0	0	0
Returns on investment cost (%)	2,33	2,48	2,87	2,94
Tube well irrigation village (Gharinda)				
Number of farmers	4	6	32	58
Average number of operational tube wells (%)	1	1	1,06	1,34
Average depth of tube well (m)	37	56	74	96
Water purchased (no.)	4	6	1	0
Water sold (no.)	0	0	0	6
Land leased out (no.)	0	0	9	17
Land leased in (no.)	0	0	0	2
Returns on investment cost (%)	3,06	3,10	3,70	3,82
Tube well irrigation village with depletion problems (Ballab-e-Darya)				
Number of farmers	32	15	32	20
Average number of operational tube wells (%)	0,41	1	0,91	1,8
Average depth of tube well (m)	46	58	67	109
Water purchased (no.)	18	2	12	1
Water sold (no.)	1	1	11	12
Land leased out (no.)	0	0	13	20
Land leased in (no.)	28	7	0	0
Returns on investment cost (%)	1,09	1,99	2,00	2,94

Key

Economic impact	Negative	Neutral	Positive
Low			
Moderate			
High			

Paths to resolving the groundwater irrigation equalities in western Ganges Basin may include reorganizing the land holdings through land reform and/or bringing the groundwater market under an effective equitable regime. A modified West Bengal tube-well and pump subsidized scheme could be adopted to enable groups of marginal and smaller farmers to independently develop appropriately specified tube wells for groundwater abstraction on their consolidated landholdings. Ideally, over the duration of the bank loan, the construction and operation of the tube wells could be undertaken by private contractors, and the farmer group would continue to receive electricity subsidies at a steadily declining rate until the loan is repaid. Ultimately, this will mean the loss of the free electricity calculated to be worth around USD 800 per hectare (Narula *et al.*, 2011), but the investment returns shown on Table 3 suggest that such approach could be viable.

4.5 Elasticity of demand – The energy equation and alternative energy sources

Many Indian State electricity boards are responsible for providing heavily subsidized electricity to the agricultural sector. The subsidized tariffs can be a flat rate based on pump capacity or metered and, in some States, waived completely. Running at a loss, the lack of capital available to the State electricity boards means the generating capacity and distribution grids are overloaded. Attempts by the generating boards to restrict the electricity used for irrigation pumping by severely curtailing the number of hours of three-phase supply while maintaining the single- and two-phase supplies were met by widespread consumer use of phase converters to reinstate quasi-three-phase supplies for their pumps (Shah *et al.*, 2008). This substantially added to surges and dips and to frequent interruptions to the supply. These deficiencies have impacted on the farmers in their selection of pumping equipment and abstraction routines. In practice, oversized pumps are used to maximize abstraction during the periods when electricity is available and to minimize motor burnout due to supply fluctuations (Padmanaban and Sarkar, 2005). A 7.5 kVa pump with inefficient thick wire motor windings is seen as preferable to an irrigator instead of a more efficient but less robust 3.5 kVa motor.

Despite these precautions, electric motor and transformer burnouts due to supply deficiencies are still common. Irrespective of the type of pump installed, burnout electric motor rewinds seldom match the performance of the new motor (Mukherji, 2007). A frequently quoted reason for over-application of irrigation water is that farmers leave the pumps switched on all the time to ensure they pump water whenever the irregular electricity supply is working.

To evade the electricity supply problems, in 2003 the State of Gujarat launched the *Jyotirgram* scheme that essentially separates the electricity supply lines to the irrigation pumps from those to other users. The scheme, initiated by an IWMI study, has enabled the State to keep irrigation supply subsidies in place while controlling pump sizes and new connections. The advantages to the irrigators are a more stable scheduled electricity supply during the 30 to 50 days of peak irrigation demand. They pay a flat-rate tariff based on pump size, which is subject to periodic escalation. Outside the peak irrigation period, only 4 to 5 hours of electricity is supplied to the pump power lines. The scheme has achieved a substantial reduction in the cost of State subsidies (Figure 9), and the removed power outages have defused complaints from the irrigators over crop losses. However, the on-going decline in groundwater levels is pushing up the energy required to lift the irrigation water to the fields (Figure 10).

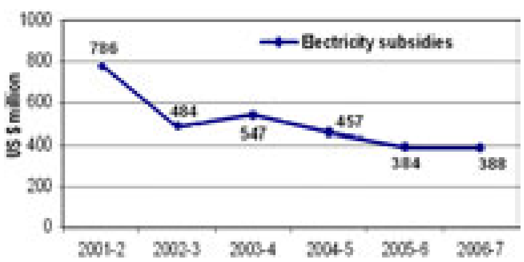


Figure 9: Decline in groundwater pumping subsidies cost to the State of Gujarat post implementation of Jyotirgram scheme (Shah, 2007).

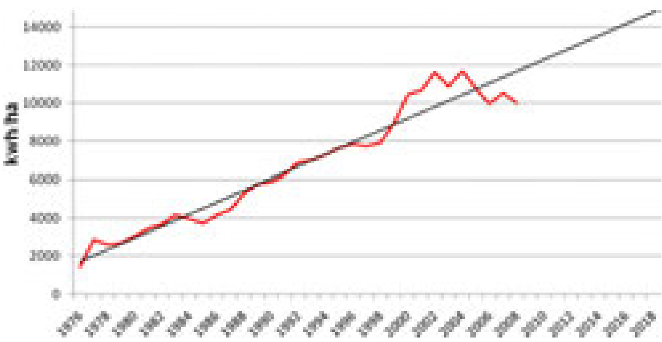
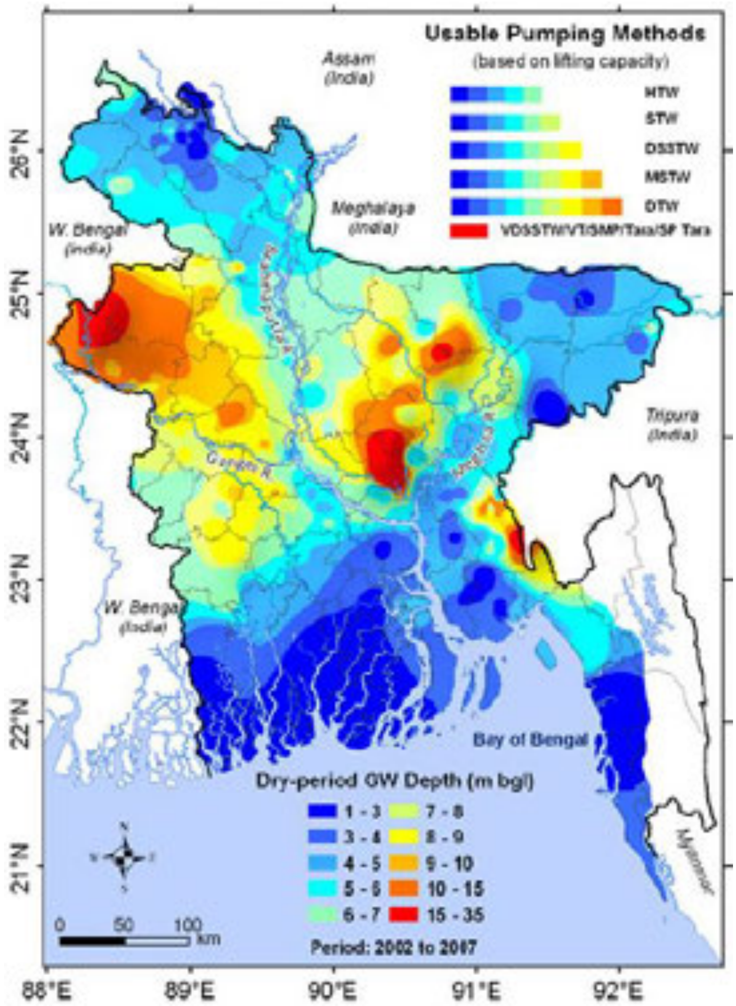


Figure 10: Gujarat – historic and projected cost per hectare of lifting 600 mm of groundwater of irrigation (from Grossman and Carlson, 2011).

4.6 Greater energy efficiency

Although the urban water-supply sector is currently the main beneficiary of the Distribution, Reform, Upgrades and Management (DRUM) project – funded by the United States Agency for International Development (USAID) – that is supporting the electricity generating boards, the problems facing irrigation farming are driven by a high consumer demand for a secure supply at a tariff that covers a fraction of the costs needed by the supplier to generate, maintain and feed a robust distribution network.



Extract from original title: "Map shows the maximum depth (m bgl) to the recent (2002–2007) static water table in aquifers in Bangladesh. This map highlights the areas where currently available pumping technologies for drinking water and irrigation water supplies are (un?)usable during the dry season. HTW hand tubewell, STW shallow tubewell, DSSTW deep set shallow tubewell, MSTW mini-submersible shallow tubewell, DTW deep tubewell, VDSSTW very deep-set shallow tubewell, VT vertical turbine pump, SMP submersible pump, Tara Tara pump, SP Tara super Tara pump."

Figure 11: Distribution of static groundwater levels across Bangladesh (from Shamsudduha et al., 2011).

Most pumps are purchased from the farmers' own resources and, given the high cost of borrowing, the majority of small- and medium-scale irrigators in India are very price-sensitive. Life-cycle costs are not seen as a rational concern when purchasing electrical pumping equipment. This has opened up the market for cheap unbranded and locally manufactured pump-sets. These often come with the penalty of poor efficiency and durability (Reidhead, 2001; Tongia, 2007). With highly subsidized tariffs, the irrigators see little need to use the electricity efficiently. This problem of low irrigation-pump efficiency came to the fore in India during the early 1990s (Sant and Dixit, 1996) and remains high on the agenda. It is compounded by the use of undersized pipes and fittings that adds to hydraulic inefficiencies.

The potential for improving the estimated 27 percent efficiency of electrical irrigation pump systems has been estimated to be 7 percent, based on a number of retrofit measures (Ahluwalia and Goyal, 2003). The areas for improvement include better foot valves, replacement of high-friction loss pipework with low-friction uPVC pipes, replacing undersized pipes and fittings, using more efficient and correctly-sized pumps, motors and drive mechanisms. The impact of pipe losses is frequently overlooked by small-scale irrigators but can quickly add to the avoidable inefficiencies of their delivery systems. The savings are expected to be in the range of 30 to

35 percent and could cut pump average annual energy consumption of 4 500 kWh by 277 to 310 kWh, However, experience from the USA (Hanson, 1988) suggests that the efficiency savings will be not registered by the electricity supplier unless there are cuts in the pumping time that match the efficiency savings: this particularly applies under flat-rate tariffs.

4.7 Suction pumps – Low-lift agrarian societies

The hydrogeological conditions that support the widespread use of centrifugal suction (rotodynamic) pumps in the shallow groundwater areas of the lower Ganges Basin (Figure 11) are found across Asia outside Bangladesh and elsewhere worldwide. Although they are being seen as route to spreading small-scale irrigation developments across hydrogeologically suitable environments in Africa, suction pumps and internal combustion engine power losses (Table 4) have to be taken into account over the highlands of Central and Southern Africa.

As the groundwater levels dropped below the range of suction pumps, users can mount the whole pump set down most hand-dug wells. However, a number of problems arise, including poor ventilation and cooling of pump motors, increased head losses and back pressures on the pump seals, vibration and difficulty in securing the pump set and finally flooding risks during high rainfall or run-off events. The historical balanced irrigation areas of Yemen have seen steadily increasing groundwater use and level declines. This has led to the replacement of the suction pumps by shaft turbine and electrical submersible pumps. Large-scale bi-lateral and international aid and loan projects since the 1970s have added to this trend.

Table 4: Effects of altitude above sea level (asl) on the Net Positive Suction Head (NPSH) and the reduction in efficiency due to the internal combustion engine power losses.

Altitude asl m.	NPSH m.	Flow reduction %	Discharge head reduction %
0	7,6	100	100
600	6,7	97	96
1 200	5,9	93	91
1 800	5,3	93	87
2 400	4,7	91	83

At the other end of the scale, NGOs developing groundwater for rural domestic and irrigation supplies employ a variety of man-powered pumps that with the exception of the treadle pump, are based on long standing designs. Based on a chain or rope pumps, treadle pumps are suitable for small-scale groundwater irrigation. Producing up to 1 l/sec they are promoted for small-holder irrigation in areas with shallow groundwater (Kay and Brabben, 2000; International Development Enterprises and Winrock International, 2002; Karekezi *et al.*, 2005; Mangisoni, 2006).

4.8 Alternative sources: solar and wind turbines

Introduced in the late 1970s (Ward and Dunford, 1984), solar voltaic pumps were initially held back by the cost of the solar panels. From the early 1980s, NGOs and bi-lateral aid grant programmes are promoting solar photovoltaic pumps (SPV pumps) and windmills as either pilot demonstration or localized development projects. These are often carried out in collaboration with specialist manufacturers. In West Africa, the Sahel region stretching from Mauritania to Niger has been the focus of a 15-year EU-supported regional solar programme– *Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel* (CILSS) – that has implemented over 1 000 borehole-based rural schemes supplying between of 5 and 120 M^3/day (Figure 12). Mali has been the main beneficiary country with around 50 percent of the small piped schemes being solar powered (Gia and Fugelsnes, 2010).

The first solar-powered water pumping systems in India were initiated under the Government promotion of non-conventional energy sources programme in 1993-1994 with an installation target of 50 000 units in place within 5 years. By the end of 2004, however, only 6 780 SPV pumps were installed (Purohit and Michaelowa, 2005). As cheaper and more efficient panels become available, solar-powered pumping is providing domestic and irrigation water supplies in many countries (IT Power India, 2006). Typical of the many pilot schemes is the combination of solar-panel and wind-turbine power generation for small-scale agriculture in Mali (Traore, 2010).

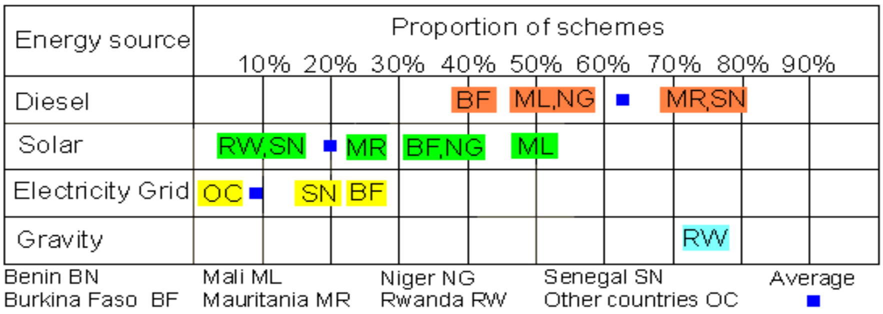


Figure 12: Energy sources for small piped water supplies surveyed in Africa (redrawn from Gia and Fugelsnes, 2010).

This indirect use of wind power generation supplements existing successful windmills powering direct-drive positive-displacement pumps in a broad spectrum of geographical settings. A number of manufacturers continue to supply these classic tripod tower windmill pumps. Freed for future fuel costs and despite the relatively high purchase and installation costs, they are used for domestic water supplies, livestock watering and small-scale irrigation. However, this trend can be expected to decline as wind-powered generators producing a more flexible electrical supply take over.

In North America, the US Department of Agriculture 2003 census lists 82 solar power pumped groundwater wells in use to irrigate 1 640 ha. The spread and rise of wind-generated electric power from 2 472MW in 1999 to 43 635MW in 2011 are shown on Figure 13. In this regard, Vick (2010) describes an analysis of hybrid wind- and solar-powered centre-pivot groundwater irrigation that shows it could be economically viable in the High Plains of northern Texas if used to irrigate two crops a year.

Earlier analyses in the 1970s and 1980s had shown the use of wind-generated power was uneconomic for a single annual crop but was economic for year round irrigation of fruit orchards. Renewed studies in the late 1990s and early 2000s showed irrigation of a single annual crop remained uneconomic, as the local electricity-generating companies were unwilling to buy the farmers surplus out of season electricity at a commercially viable rate. Based on an energy requirement of 62 kWh to pump 100 m^3, the total installed capacity needed to irrigating 51 ha of a winter wheat and summer corn crop are calculated to be 196 kW from a fixed solar array, 146 kW for a single axis panning array or a total of 150 kW wind-turbine-generated power. (A two axis panning and titling solar array was found not to significantly add to the energy output). However, annual variations in the wind and solar energy inputs in northern Texas show solar energy to be a more and more constant and consistent source of energy. Further calculations showed that combining the outputs from a 90 kW single axis tracking solar array and a 50 kW wind turbine would provide sufficient energy and improve the reliability of an irrigation system. For the calculations the height of the wind turbine hub was set at 25 m. For the systems to be fully commercial, there is a need to provide alternative conventional backup power and ideally generated surpluses to be used either on the farms, for greenhouse heating for example or sold into the local grid.

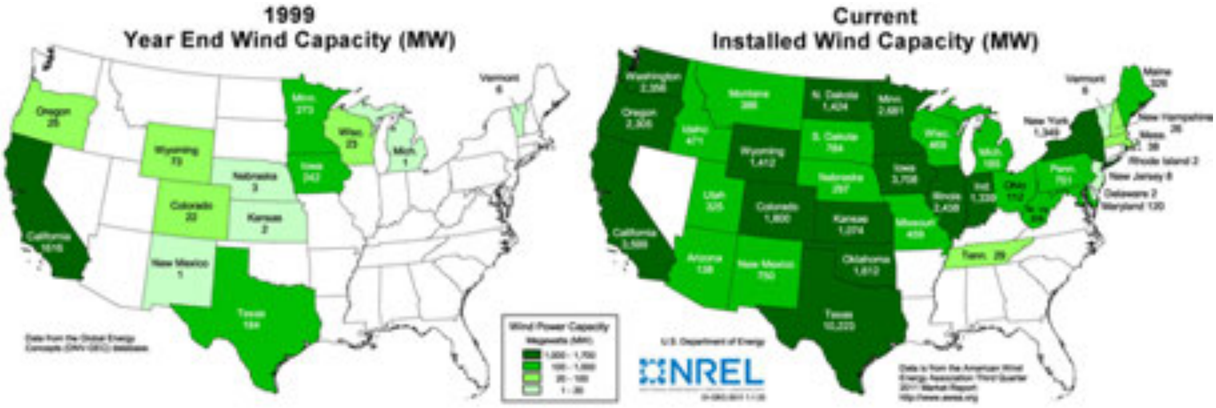


Figure 13: Growth in installed wind-powered generating capacity 1999-2011. (Adapted from US National Renewable Energy Laboratory, 2011).

4.9 Reinvigorating rural water supply programmes

The 2000 UN Millennium Summit and the follow-up 2002 World Summit on Sustainable Development set new development goals to be achieved by 2015. These included rural water supplies and sanitation as a main Millennium Development Goal (MDG).

By 1984, UNICEF, many NGOs and other agencies had moved from insular supply-side water projects to integrated health education-orientated projects involving community participation in the design, implementation, operation and maintenance of the water and sanitation elements (Bayer, 1987). The extent this could be put into practice by UNICEF and other donor agencies depended on counterpart inputs from receiving government's executive organizations. In many cases, these inputs were found to be weak or absent unless funded by the donors. When donor funds were made available, their withdrawal at the end of the project often left the client organization with well-trained staff but without recurrent funding to ensure continuing future field operations. This severely impacted on the sustainability of the project.

4.10 Improved sustainability – Community demand, management and participation keys

By the mid-1990s, mainly on NGO feedback, the views and involvement of the community demand side on the projects had become the focus of attention (Carter, Tyrrel and Howsam, 1996). Community participation was identified as the key to sustainability, typically including the election or selection of a water committee with clearly defined responsibilities, such as managing the money collected from the sale of water and organizing the operation and maintenance of the water supply system.

In the field, the effectiveness of most water committees is found to be undermined by the lack of mechanical skills, tools and access to a robust supply chain. Under decentralization reforms, tools and skills are planned to be made available at the district level, but this has yet to be widely achieved. The problems faced by the water committees can be seen with the operation and maintenance of installed hand-pumps. With the exception of rope pumps, it is widely accepted that most hand-pumps have not met the VLOM criteria.

For a successful community- and district-level-based maintenance programme, the first decision to be made is about who and how to train. Regarding who to train, many field workers advocate for the selection and training of women as they have proved competent and conscientious mechanics and have the greatest vested interest in maintaining their community water supplies (van Wijk-Sijbesma, 1998; UNDESA, 2004). The question of how to train brings in a role of the pump manufacturers and suppliers that has only been partially explored (Harvey and Skinner, 2002) but further onus to train mechanics should form an integral part of the supply chain.

Typically, up to three levels or tiers to the training programme are needed. First tier training is usually given to a responsible community member or committee. Once trained, they should be able to undertaken regular inspection of the pumps to determine if preventative maintenance is required. Although this does not require tools, it would be appropriate that the tools needed to repair the pump are held by the community water committee. The second training tier usually covers all the maintenance and repairs to the hand-pump fittings. The third tier training covers all aspects of installing and removing the hand-pump from the hand-dug or drilled well.

While ensuring the availability of spare parts should be considered by all donors, work on the supply-chain aspects shows a number of options available from a free-market solution to a fully subsidized free-supply form of distribution network. In practice the free-market solution has been found to work where the density of hand-pumps is sufficient to create a sufficient demand for spare parts. Where this condition does not exist, it has been found that some form of continued subsidized system is need. Reviews of community-based hand-pump projects, while showing a range of problems, also show numerous positive adaptive solutions to maintenance. (Harvey and Skinner, 2002; Harvey and Kayaga, 2003; Harvey, 2003).

Part 2: Diagnostic

From around 1985, many of the case histories considered in the preceding sections were based on substantial diagnostic reviews of existing and developing situations as typified by Bayer's 1987 analysis of UNICEF programmes, Black's 1998 review of World Bank-funded projects, the Trantor International's 2007 review of NORAD's Assistance to Water Supply and Sanitation in Tanzania and Kenya during the 70's, 80's and 90's, and the Giordano and Villholth 2007 groundwater irrigation compilation. The following sections, therefore, are used to attach governance issues to the diagnostic appraisals.

5. Constraints

5.1 Institutional barriers to technology access and uptake

Obvious barriers to well-regulated groundwater abstraction include:

- insufficient monitoring and knowledge of the groundwater resource being developed;
- an entrenched prior pattern of uncontrolled groundwater abstraction and usage;
- delayed recognition of adverse impacts of prior and on-going abstraction.

As pumping technology improved from the mid-19th century onwards, this pattern of barriers developed and triggered various, but often belated, governance measures. The impact of these measures on the groundwater users frequently gave rise to varying degrees of social and political backlash.

The prime governance concerns have largely crystallized around the uncontrolled use of groundwater for irrigation. Institutionally, two basic approaches to the barrier issues have been adopted. The first is the hands-off approach where the uncontrolled development continues until abstraction becomes unviable due economics, soil salinization or water quality deterioration. The second approach is the orderly application of technically well-founded, national and local water right legislation that may be supplemented with less formal institutional tools that can provide effective local resource management steps (Theesfeld, 2008), including the following:

- improving irrigation efficiency;
- defining well spacing;
- imposing a moratorium in new borehole construction;
- restricting or banning the planting of high water demand crops, notably sugar cane;
- placing temporal limits to the groundwater irrigation cycle.

Singularly, or in conjunction, each of these measures has been demonstrated to moderate groundwater level decline (IWMI, 2007b) by a number of Indian examples and by the Mexican Aquifer Management Committee programme (Garduño and Foster, 2010). To a certain extent, these mirror the Texan GMD approach in the USA. However, where these initiatives are farming community-based, they are frequently found to be fragile arrangements that breakdown with time as community priorities change or conflicting external developments provide alternative sources of irrigation water (Shah 2001).

A number of project reviews in Central America and South Asia, point out how the benefits of many donor and central government groundwater-dependent rural water-supply programmes fail to reach the poorest in the target communities, unless founded on strong community participation and transparency throughout the project formulation and execution (Sara and Katz, 1998).

5.2 Institutional barriers to efficient use of energy in groundwater pumping

Supporting the largest areas under groundwater irrigation, the USA "Big Deal" of the 1930s and the Indian rural electrification programmes of 1965-2002 had basically same objective to improve rural livelihoods by increasing agricultural production. However, there were three major differences: (i) the very low population density in the areas served in the USA compared to India; (ii) the US cost recovery tariff structure compared to the non-commercial flat rate Indian tariffs; and (iii) differences in the nature of the groundwater occurrences.

Over the 70 years of groundwater irrigation expansion supported by large stratiform aquifers in the USA, the developments have been accompanied by on-going hydrogeological appraisals and monitoring coupled with evolving legislation and management planning.

In Peninsular India, the take up of groundwater irrigation lagged behind that in the eastern States. Again driven by individual investment and subsidized electricity, the irrigation farmers' energy demands increasingly outstripped the capacity of the generating and distribution systems. In addition, the more limited nature of the groundwater occurrences resulted in sharply declining groundwater levels that further pushed up energy demands. By 2002, the agriculture sector reportedly used an average of 30 percent of the electricity generated in India to pump water[7]. Groundwater irrigation abstraction accounted for the majority of this usage. However, across Peninsular India, agricultural electricity usage approached 45 percent of the distributed power.

In hindsight, earlier and more effective coordination between the energy and agricultural planning sectors could have been desirable but given the scale of the development, this would probably have delayed the penetration of the benefits of the Green Revolution into the rural irrigation areas. Had monitoring of the developments been more integrated, part of the energy subsidies could have been diverted to a drive for the introduction of efficient irrigation methods and, as a separate issue, a combined tariff could have been devised linking the electricity and water usage.

However, to resolve the contemporary groundwater irrigation situation, a number of schemes have been implemented. From 2004, the USAID-funded DRUM and Water-Energy Nexus-Activity (WENEXA) projects have undertaken pilot schemes under the auspices of the Bangalore Electricity Supply Company (BESCOM), the Maharashtra State Electricity Distribution Company, Ltd. (MSEDCL) and the Madhya Gujarat Vij Company, Ltd. (MGVCL) in the Gujarat State with inputs from the US Department of Agriculture's Rural Utility Service (RUS). One of the findings of the 2011 DRUM-WENEXA project appraisal (Warr *et al.*, 2011) highlights the insular project approach, with little or no consultation or inputs sought from the local, state or central agencies responsible for groundwater management or agricultural development.

This omission sits awkwardly with the specific objectives of the WENEXA project that are (Warr *et al.*, 2011): "to improve co-management of energy and water resources in the agricultural, urban and industrial sectors through enhanced power distribution and end-use efficiency, coupled with sound water management practices".

However, the results from a BESCOM pilot project aimed at improving the rural groundwater irrigation energy demand side in Doddaballapur Taluk (District) near Bangalore provide concrete evidence to continue with this approach. A survey of installed pumps showed over 90 percent of the functioning pumps sets were less than 30 percent efficient. The voltage delivery of the feeder electricity lines was generally less than that required to power the pumps. Fifteen farmers received correctly-sized efficient replacement pumps in return to converting at least 0.4 ha of flood irrigated fields to drip irrigation. Most of the replaced pumps were only two years old and all were found to be oversized. Most were repaired at least once a year due to the severe voltage fluctuations. The power of new more efficient pumps was generally 1.5 kW less than the pumps they replaced. The average installed depth was 152 m and before-and-after tests showed the combined power demand of the new pumps to be 55 300 watts after six months usage. This compares with the 72 000 watts consumed by the old pumps with the water pumped in both cases remaining approximately the same. The reported overall efficiency improvements were 70 percent in terms of energy and a 60 percent reduction in water usage. However, with six of the new pump motors burnt out within nine months due to the frequent voltage

[7] DRUM training programme, 2005. Annex 1: Background note Distribution Reform, Upgrades and Management (DRUM) Project.

fluctuations, it was clear that a simultaneous upgrading of the electricity distribution system was needed and that the efficiency saving would make for a net economic gain (Mercados, 2010).

Future WENEXA work involves developing a financially viable, sustainable and replicable pilot scheme with BESCOM in the Bangalore area with the following guidelines (Mercados, 2010):

- A high quality power distribution system is required, but this may not be financially viable for the distribution utility in the current scenario of "free" agricultural supply.
- The potential electricity conservation is highly location-specific (depending on the existing equipment in the area) and time-specific (midnight savings are worth much less than peaking power), so generalization is not possible.
- Accurate metering and regular data collection are essential[8].
- Farmers' co-operation and the participation of all stakeholders.

The WENEXA results are in line with those of Lall *et al.* (2011) who calculated a potential 30 percent water saving by using similarly efficient lower-powered pumps in combination with sprinkler and drip irrigation. The sister DRUM project is undertaking a straightforward upgrading of parts of the BESCOM rural distribution feeder network (Warr *et al.*, 2011), as well as further energy audits on installed pumps. However, coupling the WENEXA approach with the secure power line upgrade delivered under the Gujarat *Jyotirgram* scheme (Shah *et al.*, 2008) should prolong the pump motor life and enable the concept of life-cycle costs to be introduced for the economic analysis of the rural farmers' financial viability.

This approach could also enable a tight time cap to be placed on the number of hours of groundwater pumping and attached to a flat-rate tariff. The hours of irrigation needed could be readily calculated from available objective statistics and varied to meet drought conditions. Any additional hours of pumping could be made subject to a surcharge. Although such an approach would probably slow the rate of groundwater level decline, reversing the trend will require a more drastic cut back in abstraction and in the area irrigated. The currently reported farming practice is that individual irrigators evaluate the irrigation water available for the coming season from pre-season water level measurements in their wells and then decide on the area to be planted (Lall *et al.*, 2011). A similar decision could be made if they were aware of an electricity cap.

In the other Indian States, variable tariffs are suggested to reduce irrigation pumping demands. The irrigation farmers in the eastern States do not receive subsidized electricity but pay close to cost price. All States, however, can implement the generating boards' DRUM-project recommendations to improve the efficiency of the pumps' electric motors and a repair-shop certification scheme to ensure the quality of motor rewinds.

5.3 Economic limits to pumping

Considered as a commodity, water has a market value based on its use, its production costs, the potential financial returns and its scarcity. In arid, semi-arid and sub-humid climatic zones where surface water is scarce or has a limited seasonal availability, groundwater assumes a high economic value. In sub-humid and humid zones, groundwater still has dominant economic advantages in the geomorphologically defined water divide and interfluve areas remote from the perennial water occurrences.

Attaching a role in governance to pumps requires consideration of the hierarchy of users. This has been framed under the pragmatic Wyoming surface and groundwater laws that are founded on a declared priority, which assigns the highest priority to drinking water for humans and animals, followed by municipal water supplies, then energy generation, transportation, domestic services, cooling and heating and finally industrial uses (Jacobs, Tyrrell and Brosz, 1995; BLM 2001). All other uses including irrigation are defined as non-preferred uses. This priority reflects the widely held highest social and economic valuation of secure drinking water and urban water supplies. In general, if the high price of tankered water supplies in the urban and peri-urban setting is an

[8] The accuracy and precision of the measurement of results achieved will vary in direct proportion to the quality and extensiveness of metering. The ideal would be the installation of reliable meters at the consumer level, but that is a controversial issue.

indicator, the limits to pumping costs have yet to be set as will be seen in the future urban developments that will be needed to resolving the water supply problems of Sana'a in Yemen where the introduction of electric submersible pumps has seen uncontrolled irrigation almost completely deplete the aquifers used for the current city water supply.

Given the lowest priority use and under most conditions, groundwater-based irrigation has high implementation and operational costs in relation to the potential profits from cropping. Groundwater irrigation is, therefore, very sensitive to the pumping costs that are directly linked to energy prices and the pumping head.

Worldwide, the vast majority of large-scale groundwater irrigation is only economically viable due to the support of significant subsidies. The energy costs for groundwater irrigation in Nebraska, USA, are shown on Table 2 above. The 2003 Nebraskan pumping costs of USD 70-75 per hectare are unsubsidized and reflect the low price of electricity, the high efficiency irrigation systems and a relatively low average pumping head (ca. 40 m). Even with this degree of efficiency, groundwater irrigation was uneconomic during the 1980s and 1990s due to low commodity prices and reduced subsidy regimes.

Field reports (Narula *et al.*, 2011) from North Gujarat in Peninsular India (Figure 10) estimate that in 2006, the energy provided for groundwater irrigation was around 10 000 kWh per hectare (unsubsidized equivalent to USD 750 per hectare). However, it is unclear whether the 10 000 kWh is measured at the point of generation or determined at the point of delivery. In the latter case, the technical transmission losses of some 30 percent and illegal connection losses at 30 to 40 percent point to an even greater demand on the generating capacity. The average power of a pump to irrigate one hectare is 7.5 kW. This suggests that the pumps are operated for the equivalent of 55 days continuous operation. If similar energy consumption levels are substantiated across the rest of Peninsular India – and indications suggest that this is the case, then the economic limits of groundwater pumping may have already been reached.

In the Ganges Basin, Scott and Sharma (2009) provide further energy data for the lower head irrigation areas that shows annual pumping costs to range from USD 150 to 250 per hectare. Despite the lower costs, there are no completely depleted aquifers, and neither has land been lost to soil salinization nor has saline intrusion occurred.

Elsewhere, propelled largely by subsidies, the planned or unplanned expansion of groundwater irrigation underpinned firstly by low cost suction pumps and, then, by deep well turbines and submersible pumps has seen alarming declines in groundwater levels in many countries. Where the energy supply for groundwater irrigation is unsubsidized, the crop value ultimately dictates the viability of the farming. In parts of Texas, USA, irrigated lands are being declared as uneconomic due to pumping costs. More frequently encountered reasons for abandoning groundwater irrigation are salinization of the land and the intrusion of saline water. Large tracts of irrigation land have been abandoned due to these causes.

No development sector shows the flexibility of the economic limits to pumping more clearly than in the deep mining of metallic minerals. An emphatic rise in copper prices has enabled the Konkola copper mine in Zambia to remain viable. Some 350 000 m^3/d of groundwater is pumped from >1 500 m below ground level to dewater the workings in one of the wettest deep mines in the world (Engineering and Mining Journal, 2011).

6. Scope for Securing Social and Environmental Benefits through Governance

6.1 Access to well informed technology options

The social and environmental benefits associated with the rural and urban water supply sectors are well established but remain to be maximized by parallel developments in the public health and sanitation programmes. Frequently, the responsibility for water supply and sanitation development rests with separate ministries or agencies. The problems this causes are understood and are being addressed at the community level but are being less well addressed at the funding level.

With access to the internet, it has to be assumed that the operators of large urban water supplies and pumping equipment agents and importers are fully informed of the improved pump performances derived for research into hydraulic design, materials and controls. With the current high power, rotation speeds and vane tip velocities, pumping heads of 850 m are being achieved by the latest single stage centrifugal impeller pumps. Computerized design studies using Computational Fluid Dynamics software (CFD) suggest an ultimate single stage 1 000 m head limit within the current level of technical knowledge.

Development of materials includes low friction internal pump coatings and the use of ceramics, tungsten and silicon carbides to reduce wear rates and to improve the performance of shaft seals. The benefits of wider use of variable speed controls to control pumping volumes include optimization of energy use and can reduce pump wear. Computerized condition monitoring provides a useful tool for programming preventative maintenance. There is also continuous assessment of improved electric motor designs including the use of the brushless inductive axle flux drives. The cost-benefit from this research to the prospective users, however, may be relatively low and therefore, may not merit follow-up unless driven by national and international energy efficiency legislation.

The situation with hand-pump research is largely static as the problems with reciprocating cylinder pumps seem technically intractable. Achieving the VLOM concept remains unlikely until the skill levels available within or to rural communities are sufficient to undertake expedient repairs to broken down pumps. The wider use of the treadle pump, however, highlights the effectiveness of the rope (or chain) pump that has been widely used for rural community water supplies in Central America and China. Also known as the Paternoster Pump and the Liberation Wheel (pump) in China, the efficiency of rope pumps ranges between 50 and 70 percent (Fraenkel and Thake, 2006). This is comparable to the reciprocating cylinder pumps. With the additional benefits of low cost, simple technology and easy maintenance, the rope pump demands further consideration. Although best suited for hand-dug wells there is scope for developing slim line rope pumps to fit 150 and 200 mm diameter boreholes. The rope pump also lends itself to retro-fitting of electric or diesel motorized power.

A further motorized pumping technology that shares the simplicity advantages of the rope pump is the combination of a surface mounted centrifugal pump and a down-hole jet or ejector pump. With no down-hole moving parts, jet pumps are more efficient than airlift devices. They are most suited to low volume domestic water supplies where efficiency is not a paramount consideration. They also provide an interim solution to maintaining water supplies in areas where water levels are dropping below the range of suction-lift centrifugal pumps in line with the stepped development model recommended by Sounders and Warford (1976).

The technological options available to improve groundwater irrigation cover the abstraction and application efficiencies, and the crops and cropping pattern (Golden, Peterson and O'Brien, 2008). The contribution of improved pump design and construction in terms of efficiency, low maintenance costs and working life is equally available to irrigation farmers if they have the capital to upgrade their abstraction. Although this is the case in the commercial irrigation farming areas of North, Central and South America, Europe and parts of Asia and Australia, the small rural irrigators with holdings of less than one hectare lack the necessary capital and, if dependent on electricity for pumping, face two further problems: they usually are competing with neighbours for water from a common source aquifer and for electricity supplies from a tenuous distribution system.

In practice, these rural irrigation farmers have little incentive in acquiring efficient pumps instead of their more robust oversized pumps. This becomes even more justified where they pay a low flat tariffs or no tariff at all for the electricity supply. However, they do have options to improve their irrigation application efficiency, to grow crops with lower water demands and to modify their cropping pattern. Where farmers previously attempted to crop three times a year, when they adopted the first two options they frequently cut cropping to twice a year.

Ultimately, declining groundwater levels due to irrigation abstraction can be controlled or resolved by:

- introducing an equitable water rights scheme that positively discriminates in favour of the small landholder abstraction;
- placing limits to allowable borehole pump sizes compatible with the scale of the groundwater occurrence being exploited; or
- waiting until pumping of groundwater becomes totally uneconomic even with free electricity.

Given the last outcome is incompatible with the need to ameliorate rural livelihoods, the short term solution remains in improving the reliability of the energy supplies, pump efficiency and introducing an appropriate quantity based limits to abstraction and area irrigated.

6.2 Energy efficiency programmes and groundwater pumping

The vast majority of modern pumps designed to abstract groundwater are powered by internal combustion engines or electric motors. Current diesel energy efficiencies peak at around 45 percent while industrial testing suggests average efficiency clusters around 25 percent. Improvements to internal combustion engine efficiency will stem from their widespread use in transportation, and peak diesel engine efficiencies are predicted to improve to 55 percent in the foreseeable future. Irrespective of these improvements, the variable efficiency of non-branded diesel-powered pumps requires scrutiny and regulation to ensure they approach the performance of the most efficient equivalent pumps on the market.

As electric motors use about 70 percent of the general industry electricity demand, they are the focus of European Union and other regulatory body's efficiency directives. The efficiency of induction electric motors is directly related to their rated power output as shown on Table 5. It also varies with the load as shown on Figure 14.The price premium of the most efficient motors is between 10 and 30 percent[9]. The market penetration of lower-powered motors (>3 kW) meeting these standards in the UK is less than 10 percent. While the hydraulic and mechanical efficiency and durability improvements are shared by both electric and internal combustion powered pumps, the overall energy efficiency ranges from 40 to 75 percent depending on the pump size and number of stages.

The application of Variable Speed Drives (VSDs) to fluid pumping in the European Union is identified as the motor system technology having the highest significant energy savings potential as shown in Table 6. The current applications of VSDs to groundwater pumping from boreholes are limited to highly-engineered urban and industrial water supplies where Pulse Width Modulation (PWM) control technology (Figure 16) can be used to produce a constant flow rate, pressure, pumping head or temperature[10].

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[9] BNM02: Minimum Efficiency Performance Standards (MEPS) for electric motors. UK Defra v3, 2007.
< efficient-products.defra.gov.uk/spm/download/document/id/653 >

[10] See 2008 Grundfos SP Engineering Manual, available online from http://www.grundfos.com/content/dam/Global%20Site/Industries%20%26%20solutions/waterutility/pdf/engineering-manual.pdf.

Table 5: Nominal relationship between electric motor power and efficiency

Power kW	Efficiency
0,75 – 3,0	78,8
3,75 – 6,75	84,0
7,5 – 14,25	85,5
15,0 – 36,75	90,2
37,5 – 100	91,7

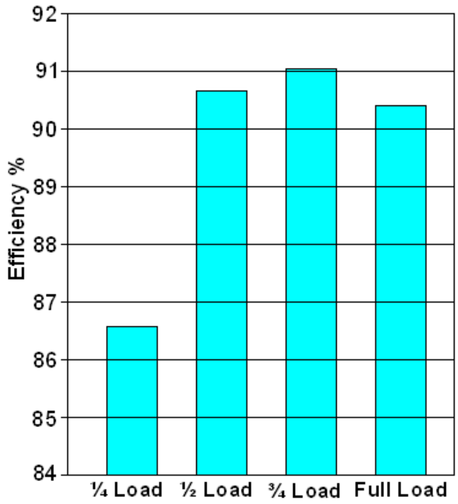

Figure 14 (right): Relationship between a Minimum Efficiency Performance Standard (MEPS) 7,5 kW electric motor working load and efficiency.

Unaddressed in India as a whole, unrestrained groundwater pumping coupled with irregular electricity supplies is possibly causing some 80 million km^3/year of excess abstraction for irrigation. This is based on the estimated groundwater abstraction of 150 km^3 in 2003 reported by Sharma (2007) compared with the CGWB's reported 231 km^3 for 2004 (CGWB-MoWR, 2006). More recent estimates of the total groundwater abstraction for irrigation hover around 200 km^3 (Aguilar, 2011, citing Ananda, 2009). This still leaves a reported in-balance over the CGWB's 231 km^3 that is in the order of one fifth of the mean annual flow of the Nile into the Mediterranean before the construction of the Aswan High Dam.

Table 6: Assessment of potential for energy savings by applying VSDs pumps in the European Union VSDs Pumps (from De Almeida et al.*, 2000).*

VSDs	Average Savings %	Applicability %	Already Applied %	Technical Potential %
Pumps	35	60	9	51

Irrespective of the availability of absolute abstraction figures, most field studies point to inefficient and over application of irrigation water in the rural areas linked to the electrical distribution networks. In Peninsular India, the largest area of unsustainable groundwater abstraction, the situation has reached crisis point. Groundwater levels are fast dropping beyond the reach of many of the small farmers' wells and pumps while the larger landowners drill deeper and install more powerful pumps to continue with the exploitation of the resource. In addition, as the groundwater occurrences approach depletion, contamination of the groundwater is occurring due to coastal saline intrusion or because poor-quality virtually connate groundwater is tapped.

However, the problems in Peninsular India are being addressed by the on-going DRUM and WENEXA programmes and the *Jyotirgram* scheme in Gujarat. These along with the University of Columbia Water Center initiative (Narula *et al.*, 2011) show the need for more coordination between the energy and agricultural sectors, if secure energy supplies and improved irrigation practices are to stabilize or modulate the groundwater level trends and improve farmers' real incomes. Equally significant is the demonstrated potential 30 to 70 percent reduction in the energy demand if the electricity supplies can be stabilized and secured (Ahluwalia and Goyal, 2003; Padmanaban and Sarkar, 2005; Shah, 2007a; Shah, Bhatt, Shah and Talati, 2008).

6.3 Reducing emissions

Other estimates of the energy savings achievable by agriculture demand-side management range from 40 to 45 percent (Warr *et al.*, 2011). If achieved, given the high agricultural electricity use, these savings will have significant impact on the ongoing emissions output of the Indian thermal generating capacity shown on Table 7.

Although water utility and industrial pumping greenhouse gas (GHG) emission assessments are the subject of national and international directives, GHG emission assessments for groundwater irrigation are still largely unexplored. However, carbon taxes could be applied to the pumping equipment but they are surely better rolled up with energy price especially as the larger pumps are considerably more efficient than smaller pumps (Table 5).

Table 7: India installed generating capacity, October 2010 (Warr et al.*, 2011).*

	Thermal MW & (%)				Nuclear (MW)	Hydro (MW)	Renewable (MW)	Total (MW)
	Coal	**Gas**	**Diesel**	**Total**				
All India	89,778 (47%)	17,625 (17%)	1200 (1%)	108,603 (65%)	4,560 (3%)	37,328 (22%)	16,787 (10%)	167,278

6.4 Institutional environments that can work – Economic and environmental regulation

Halting or reversing the declining water levels across Peninsular India also requires emphatic political action including addressing existing property rights law to ensure equitable distribution of the groundwater resources to all landowners (Aguilar, 2011). The electricity suppliers are entitled to control connections to protect the integrity of their supply and to set tariffs in line with national development objectives. In parallel with scientific assessments to quantify an appropriate annual rate of groundwater abstraction, consideration of the status of prior appropriation rights in lands classified as under tribal control may yield a basis for assigning water rights.

Existing Indian environment priority legislation could possibly be applied to set limits to the size and performance of installed pumps together with setting a minimum distance between dug and drilled wells. In the case of farmers with very small landholdings, they could be encouraged to consolidate their resources to qualify and share an irrigation pump. The use of this legislation would be in line with the 2000 Millennium Declaration concerning the protection of the environment. The political solution to the objections made by medium- and large-scale farmers facing a large reduction in their current abstraction may lie with the introduction of subsidized agricultural processing plants and distribution networks that will encourage a shift into higher added-value horticulture produce grown on reduced irrigation areas.

Although the post 2002 expansion of groundwater irrigation in the State of Nebraska, USA, for biofuel crop production is regulated by the State groundwater legislation, the farmers and cooperatives are further protected by the Initiative 300 legislation[11] that is specifically designed to prevent the spread of major out-of-state agro-industrial corporations into the State. Initiative 300 was decreed in 1982 with the objectives of protecting the land from the environmental damage caused by corporate farming observed in other States in the USA. In particular, Initiative 300 was designed to forestall corporate skirting of their liabilities for the damage caused by their farming activities. This was prompted by an earlier phase of groundwater fodder irrigation for ranching developments undertaken by out-of-state corporate-driven speculation in the extensive Sandhills region of Nebraska. The irrigation fields were created by bulldozing the tops off the wind-blown sand dunes into the depressions. These developments started in the late 1960s and relied on centre-pivot groundwater irrigation. Many of the agro-industrial corporations were bankrupted by the 1980s decline in farm produce and cattle prices, and the abandoned farms, stripped of vegetation cover, suffered extensive wind erosion (Kepfield, 1993; Decision Analyst, Inc., 2003). Currently, Initiative 300 is being challenged by a new wave of agro-industrial corporations.

Although small-scale groundwater irrigation is being widely promoted across Africa, the take-up is limited. There is a strong possibility that uncontrolled development could rapidly reproduce the negative impacts observed across Peninsular India. To a very large extent in sub-Saharan Africa, the possibilities for groundwater irrigation-based industrial-agricultural systems are limited in comparison to the very large scope for small-scale farm irrigation in the humid and sub-humid zones. Given the nature of many of the groundwater occurrences in these zones, a prudent blanket permits an abstraction limit of 1.5 l/sec per km^2 to be applied until the resources are fully monitored and evaluated. While this will enable the use of two-phase electric motors or small low-powered diesel pumps, larger developments should be only considered as a second phase development, to be started after several years of groundwater-level data has been collected and assessed. Equally the use of solar- and wind-powered pumps merits wider consideration.

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[11] See Center for Rural Affairs website for more information on Initiative 300 (http://www.cfra.org/I300/factsheet).

Policies should aim at efficient use of the water by subsidizing the introduction of dry-season drip irrigation of around 2 ha and supplementary wet-season irrigation of 5 ha rather than permitting the use of bigger pumps and inefficient basin or furrow irrigation. With the demand for cheap pumps likely to continue to grow among the agricultural and livestock-based rural communities, national governments and funding agencies should seek to define and impose efficiency standards for imported and locally manufactured pumps and power units. Where rural electrification is in place, the network operators should collaborate by producing lists of approved and certified pumping equipment.

6.4.1 Rural water supplies, securing sustainability

Given the high MDG priority, providing sustainable drinking water supplies to rural communities has proved far from straightforward, with the hand-pump at the centre of many of the sustainability problems. Historically, hand-drawn water abstraction has had little impact on the resource base. The main development problems have been locating the groundwater and protecting it from contamination. In the humid and sub-humid tropics, most rural communities are sited along the local water divides where typically the groundwater saturated zone is thin and borehole yields correspondingly low or negligible. This even applies in the river basins of the Lake Victoria Basin in Kenya where the annual rainfall is over 1 500 mm and across the granites of the Central Region of Ghana.

At the beginning of the IWSSD, some donor projects moved into communities, constructing boreholes and wells equipped with hand-pumps with the minimum of consultation, and in the worst-case scenario no provision was made for repair or maintenance of the pumps, nor was the ownership clearly defined. Frequently this project model worked on the assumption that each hand-pump would serve populations of around 300 and that larger villages could be supplied with several pumps. With a matter of one or two years, at least 30 percent were broken down with failures often traceable to poor original installation (Jones 1990; Michael and Gray, 2005).

6.5 Institutional environment – Setting development standards

By the 1990s, many governments outside Europe and North America through national water acts, organized and empowered public and private agencies to develop urban and rural water supplies. They also imposed design and service standards.

Coupled with the World Bank push for decentralization, the Ghanaian Community Water and Sanitation Agency (CWSA) responded by preparing a series of design and construction standard guidelines, as well as operation and management manuals (CWSA, 2004). One set covers the provision of water supplies for small communities and the second set, small town piped-water supplies. Although fully justified in seeking to ensure well-engineered systems and compatible service levels across the country, certain derogations have been found necessary to optimize the supply systems. The final objective of the sector reform is that District level offices will assume full responsibility for the design and construction of all community water supplies.

The small community water supplies are generally based on drilled wells and hand-pumps and the work is most often executed by local community groups, NGOs or under bilateral grant projects. The small-town water supply projects are usually part of larger bilateral or multilateral loan or grant programmes employing qualified consultants and contractors to design and construct the electromechanical, transmission, storage and distribution works. There are only a few NGOs bridging projects that follow a sequential series of small improvements as identified in Box 7. These intermediate schemes are usually based on innovative mini-hydro, wind generators and solar power.

An early step in both sets of the CWSA guidelines is the establishment of a community water committee (board) that will take over full management after the commissioning of the works. Notionally, they will be supported at district level by water supply teams once the immediate shortages of trained manpower are overcome. However, given community problems in maintaining hand-pumps, future greater problems can be foreseen in the maintenance of borehole pumps and electromechanical equipment, unless the local supply chain is soundly established. The guidelines for small-town water supplies require the equipment suppliers to have local agents capable of providing after-sales services and relevant training support to the communities and to water sector professionals. In practice, this does not yet appear to have happened on a large scale. This raises serious concerns over the future sustainability of the systems unless the local supply chain is improved and there is more intensive training of technicians and engineers.

Another weak link in the CWSA guidelines is also found worldwide. This is the chronic non-payment of water charges by state and parastatal institutions: schools, clinics and advisory offices are almost universally in default. This is being addressed in Kenya where, in 2011, regional offices of the Water Resources Management Authority are enforcing payment of water right charges to the extent that school, industrial and urban water supply boreholes have been shut down.

6.5.1 Institutional decentralization, maximising the success

Other development models stemming from the World Bank decentralization initiative involve the Public-Private Partnership (PPP) programmes reviewed by Gia and Fugelsnes (2010) and listed in Table 8.

Table 8: PPP water supply programmes –stakeholder profiles (adapted from Gia and Fugelsnes, 2010).

Country	PPP initiated	Asset holder	Regulating authority	Water provider profile	Number of operational PPPs 2009	Performance monitoring system
Benin	2006	Local Government	Ministry	PSP	130	TBI
Burkina Faso	2009	Local Government	Ministry	PSP	125	TBI
Mali	2006	Local Government	Ministry/Region	PSP	20	STEFI
Mauritania	1994	Central government	Region	PSP:ANEPA	350	CMSP
Niger	1990	Local Government	Ministry	PSP	298	BCC
Rwanda	2004	Local Government	Region	PSP	230	TBI
Senegal	2000	Central government	Ministry	CBO	183	MANOBI

Key: Providers: PSP - private sector participation, ANEPA (Mauritania) - monopoly non-profit association, CBO - community based organization. Performance monitoring – these broadly are designed to ensure business based cost control and recovery.

The scale of these developments bridges the small-community and small-town piped-water supplies as shown in Table 9.

Table 9: Water supply scheme profiles (adapted from Gia and Fugelsnes, 2010).

Type	Characteristics	Population served	Network length	Storage capacity	Production capacity
Single public water point	No distribution network, ground or low level storage	500-1 000	< 0,1 km	0-10 m^3	5-10 m^3/day
Multiple water points	Limited gravity distribution network, limited low level storage	200-2 000	< 2 km	10-50 m^3	5-40m^3/day
Multiple water points, institutional and household connections	Extended piped gravity distribution. High level storage	2 000-10 000	2-10 km	10-50 m^3	20-300 m^3/day
Multi village schemes	Large piped scheme with long transmission lines between villages	5 000-200 000	10-250 km	10- 50 m^3	100-2 000 m^3/day

The rationale for establishing the PPP model was similar to that behind the Ghanaian CWSA guidelines. However, in the seven countries reviewed, the community water committees had no legal standing and had not received sufficient guidance or expertise to undertake the community-level operation and maintenance tasks and, even with the PPP schemes in place, they have been found to suffer from the same resource and expertise problems as those found in countries with strong community management programmes in place. In addition, the PPP schemes are heavily reliant on a robust and competitive contracting and service-operating sector. Both approaches share the same governance difficulties and without the trained national manpower and local support funding, they are only partially delivering immediate benefits to the rural populations.

Major urban water utilities tend to have strong technical departments and work closely with pump manufacturers and suppliers to optimize the energy consumption. For their groundwater abstraction they rely on their own specialized engineers or qualified sub-contractors to operate and maintain the pumping equipment. The reliability and efficiency demands of the urban water operators and commercial groundwater irrigators ensure a competitive market among borehole-pump manufactures. These operators focus heavily on lifetime cost analysis.

When weighing the balance between the main cost components – energy usage, maintenance and repair, loss of production, purchase and installation, operation, decontamination and removal – commercial groundwater irrigators have always focused on the potential loss of production costs in terms of loss of crops. As they are selling their output on an open market, the commercial irrigators can pass on rising energy and other production costs. The situation is different with the regulated urban water-supply companies, as these have appropriate backup systems to ensure continuous supply and have limited opportunity to immediately pass on rising energy costs.

7. A Rationale for Managing Demand

7.1 Absorbing actual costs at the point of supply – Spreading risks

A legacy of the rapid growth in piped urban-water supplies since 1850 is the need to generate operational and investment capital to develop new raw-water sources, to continuously maintain, upgrade and extend the treatment and distribution systems and to provide surface and waste water sewerage disposal systems. Historically, the major water companies adopted one of two charging strategies: either a flat rate charge or a charged based metered water usage. In the groundwater-stressed areas of southern England, flat-rate charging is being replaced by a sliding-scale metered usage rate. Most countries enforce water quality and pricing legislation in recognition of its importance to the common good.

Where small town water supplies are implemented under the decentralized sustainable models as seen with the Ghanaian CWSA programmes, the water charges are planned to meet the running costs, system maintenance and future expansion. Numerous willingness-to-pay surveys provide consistent evidence that rural and peri-urban communities are able to cover the basic water-supply operation and maintenance cost. However, analysis of a limited number of post completion project reviews shows considerable disparities between the performance of the community water boards with regards to financial and technical management of the resources needed to expand the commissioned water supplies: this situation is likely to improve as district- and community-level expertise develops.

Under the rule-of-capture doctrine, urban- and rural-supply operators can secure groundwater abstraction rights by appropriate land purchase: in areas of competitive groundwater usage, the land area needed can be large. This can be seen across the High Plains aquifer in the States of Texas and New Mexico, USA (Figure 15). Under other water-right doctrines, the urban and rural groundwater supplies are granted and protected from competitive users by national or state legislation: the protection from well off-setting reduces the area of land needed to be owned by the operators.

Despite obvious differences, the irrigation farmers in the State of Nebraska, USA, and in Peninsular India have invested in developing groundwater sources and rely on the productivity of their lands. The Nebraskan farmer investment and income is geared to prevailing commodity prices and shifting market conditions: past downturns in commodity price have seen farmer retrenchment and agro-industrial corporate abandonment of speculative irrigation lands.

Across the less favourable hydrogeological terrains of Peninsular India, a large number of farmers have independently and competitively exploited the common-pool groundwater resources (Strand, 2010). With unrestrained abstraction rights based on the rule-of-capture doctrine, the farmers have little or no conservation incentives when confronted by excessive drawdowns caused by overlapping cones of influence for nearby pumping wells and boreholes. Without legislation modifying the rule of capture that removes the concept of private ownership of the groundwater, there is no scope for charging for the groundwater either directly or probably indirectly.

As already outlined, a widely accepted solution to the over-abstraction is upgrading the electricity distribution networks to the well heads, replacing the flat-rate tariffs with fully commercial rates and an appropriate supply rationing schedules together with the introduction of efficient pumps. In practice, many marginal (landholding less than 0.4 ha) and small farming households (0.4 to 1 ha) are unlikely to benefit from these developments unless encouraged to pool their resources.

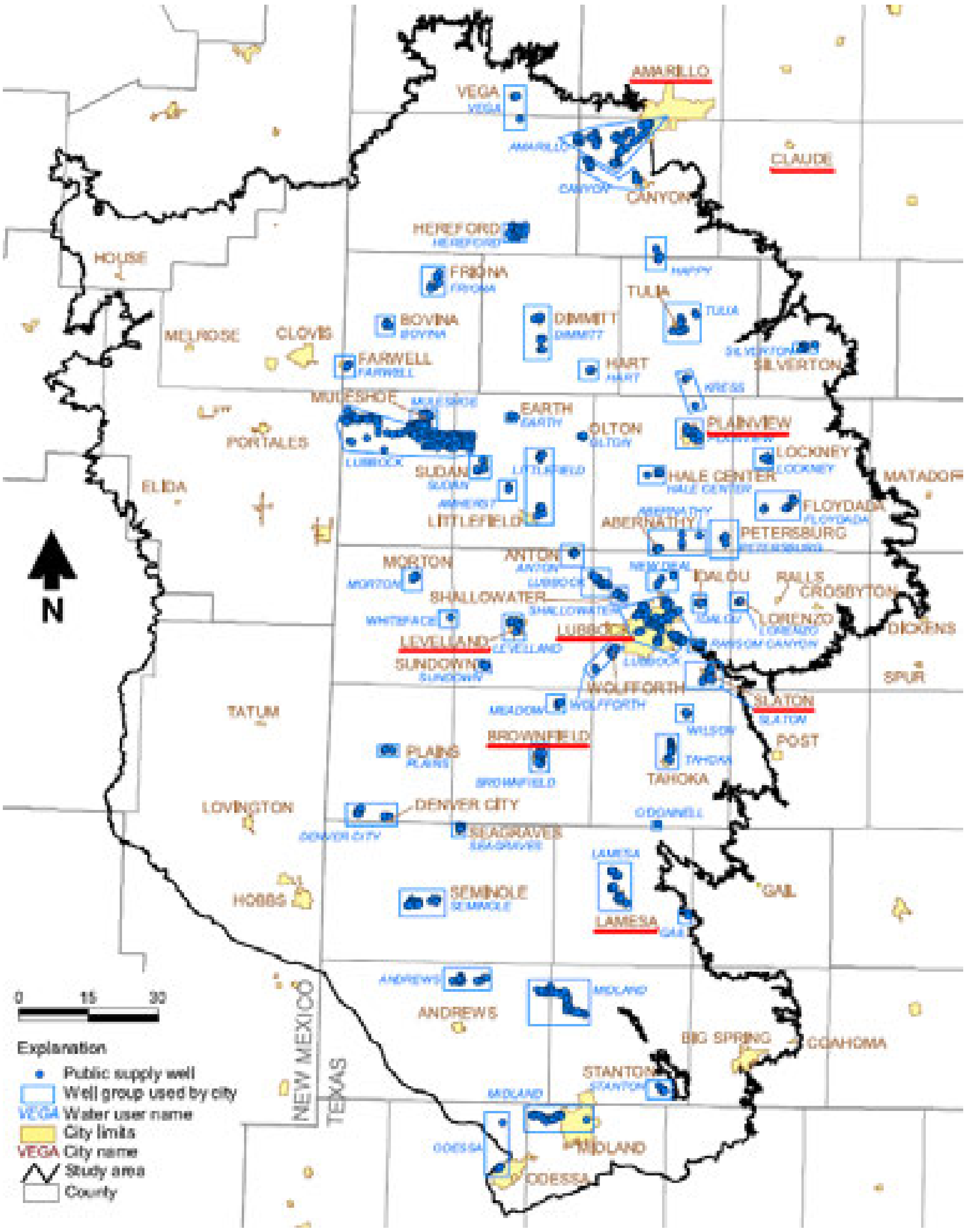


Figure 15: Texas and New Mexico southern High Plains Aquifer, urban groundwater supply sources. (Canadian River Municipal Water Authority (CRMWA) cities underlined in red). (Adapted from Blandford et al.*, 2003.)*

Part 3: Prospects

8. Projected Evolution of Pumping Technology and Cultures of Use

The current groundwater-pump market ranges from rural water supply hand-pumps, through low-powered mechanized pumps for small-scale rural and urban water supplies, to powerful electric submersible pumps for urban, irrigation, industrial and dewatering purposes.

Competition for natural resources is reflected by rising energy costs disproportionately outstripping most commodity and consumer prices. This is expected push energy efficiency higher when considering pump selection criteria. All end users expect their pumps to be efficient, durable and easy to service and operate, with minimal downtime. Amongst most informed users, the purchase price is of much lesser consideration than meeting these requirements.

Looking at the trends in the uptake of largely unregulated groundwater-based irrigation points suggests these technological developments are going to be tempered by increasing energy costs so that indirect factors are more likely to play a role in affecting regulation of groundwater abstraction.

8.1 Rural water supplies, meeting the sustainability targets

At what can be considered the bottom-end of the market, the hand-pump continues to prove an exception. Sustainability and downtime are the key selection aspects. Even with full involvement of communities through water committees, many installed hand-pumps continue to remain out of service for many weeks or months. In some cases, working parts have come to the end of the service life but more frequently there has been a premature failure of a vital part due to a manufacturing or design fault or poor pump installation. These inherent defects have been widely documented and although they should have been remedied by quality controls and inspections, in practice these are seldom enforced.

The situation is aggravated by the hands-off procurement policies adopted by most donor agencies. Numerous published and unpublished reports recommend donors should use their purchasing power to demand full compliance to manufacturing standards and to follow up the provision of training and after sales services. It is also widely recommended that the donors should provide longer term funding to establish a sustainable maintenance system. This funding should extend to covering all associated costs including transport and field allowances. In too many projects such funding ends immediately after commissioning of works.

On the design side, re-engineering of the India Mk2 and Mk3 pumps chain linkage between the pump rods and the quadrant can be considered. The use of a longer pump cylinder for example has the following advantages as it increases the piston setting-depth tolerance and if the initial setting is towards the bottom of the cylinder, this would enable the pump rod at the quadrant end to be cut and re-threaded. A second modification to eliminate the inherent difficulties of cutting threads in the field could be overcome by supplying either a fully threaded pump rod or supplying a selection of pre-cut and threaded rods of different lengths so the piston can properly located in a longer cylinder.

The implementation of the rural and peri-urban small-piped and small-town water supply schemes lags behind the MDG water target. The WHO/UNICEF, 2011 thematic report on drinking water 2011 concludes that: “at the current rate of progress, this still will leave 672 million people without access to improved drinking water sources in 2015, and possibly many hundreds of millions more without sustainable access to safe drinking water”.

8.2 Improving low-lift irrigation livelihoods

Also at, or close to the bottom end of the market, the profusion of low-powered, motorized pumps available for the rural domestic and farmer water supplies have a mixed record for durability and efficiency. Although given time, brand leaders in terms of customer satisfaction will emerge, in the near and mid-term, the interest of the low-income rural consumers should be protected by a certification system. Indeed, a formal internationally recognized testing and certification scheme is desirable for all groundwater and irrigation pumping equipment manufactured for sale under subsidized schemes or on the open market.

When groundwater levels drop below the range of suction pumping, small-scale subsistence irrigators that have experience with and own, or hire, centrifugal pumps can turn to deep-well ejector pumps that provide much cheaper alternative to the more expensive and difficult to maintain line-shaft turbine pumps. Although the 20 to 30 percent pumping efficiency is down compared to the line shaft pumps, the benefits of having all the moving parts on the surface makes for easy maintenance. Also, if flexible hose is used, the ejectors can be readily removed from the well or tubewell for servicing or replacement.

With landholdings of less than 0.4 ha, the main buyers or hirers of small motorized pumps for irrigation cannot afford a gap in their water applications during the growing season. If a breakdown occurs, they can be forced to purchase water from surrounding irrigators or water suppliers unless they have an alternative manual pumps installed. If they were using motorized rope pumps, they could revert to a treadle mechanism to lift water to their fields. As with ejector pumps, the simplicity and ease of maintenance are the obvious advantages.

A further step available to improve both low-lift and high-lift small-scale groundwater irrigation is the use of mini-centre pivot systems by marginal and medium scale farmers in Asia and elsewhere. Currently USA manufacturers[12] are producing 27-30 m radius systems that cover around 0.25-0.4 ha. The motorized arm rotation can be solar or battery-powered. Given the economies of large-scale manufacture, the wide range of sprinkler application rates available and up to 1.8 m clearance, these systems could be considered instead of fixed sprinkler systems being proposed for cereal cropping. Combining mini-centre pivots with the research into the use of tensiometers in flood irrigated rice fields in the Punjab State, India, (Polycarpou, 2010) should demonstrate very significant water savings.

8.3 Easing the community technology load

Groundwater developments for small-town supplies are a focal point for the many MDG projects. Using small-town water supply is shorthand to describe piped distribution schemes designed to deliver 20 litres per persons/day via communal standpipes and 60 litres per person/day to house connections for communities with populations between 2 000 and 50 000. Most new schemes will follow the established development model of employing engineering consultants for the design and supervision and using qualified contractors for construction.

While the schemes are frequently devised and negotiated by central or regional government, under decentralization, commissioning and supervision of the work are undertaken at the district and community level. Analysis of this approach suggests that donors could adopt a hybrid project model as a possible way forward. This envisages a donor-funded technical assistance team designing and supervising the construction of the more technically demanding system components, the borehole drilling contract, the electro-mechanical pumping equipment, the transmission mains and the storage tank, and leave the community and the district offices to design and construction of the distribution system from the storage tank.

Regarding the availability of spare parts and technical skills, the advantages of equipment standardization are widely recognized (UNICEF, 1999). Establishing a spares exchange system where broken parts are exchanged for guaranteed refurbished parts can be considered. This should reduce the time pumps are out of service.

[12] See Lindsay Manufacturing website (http://www.lindsaymanufacturing.com/green_center_pvt.asp).

9. Prospects for Managing Groundwater Demand at the Point of Abstraction

Several post-commissioning, management models have been adopted for the operation and maintenance of public borehole supplies. Under full decentralization, community water boards are established with full responsibility for revenue collection and handling of funds used to cover future scheme operation, maintenance and expansion. The community water boards have the option to undertake this work directly or using private companies under contract. Other models include local government management through regional water supply agencies or more centralized government water supply operators responsible for all the small towns in the country.

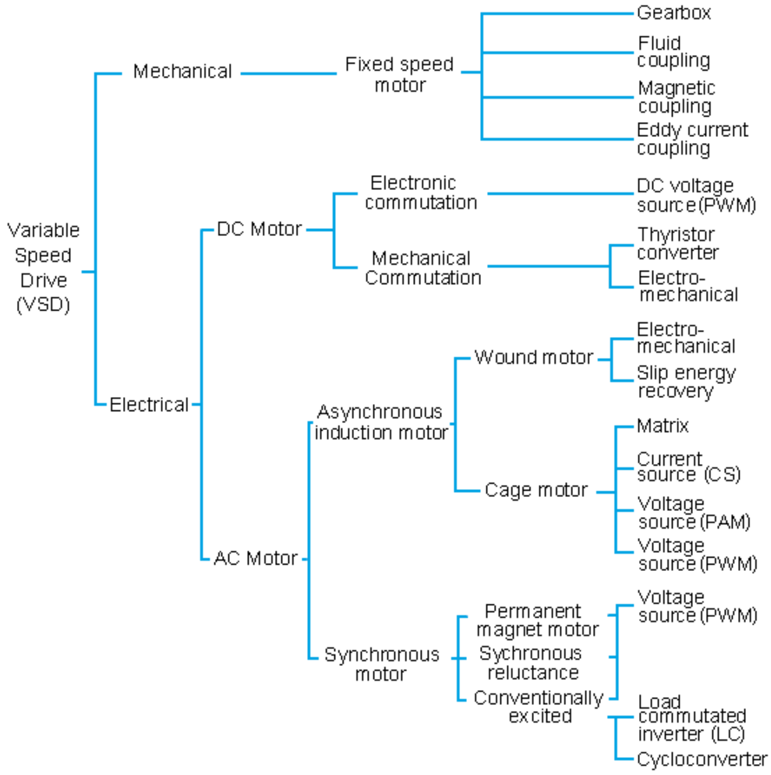
In addition, more effort needs to be directed to collection of long-term groundwater level data. It is in the community water boards' interest that long-term groundwater monitoring should be started as soon as possible in order that the local aquifer response to abstraction is adequately recorded. Such information will be invaluable should the town abstraction exceed the sustainable yield of the aquifer. It will reveal any long term declines in the groundwater level and firmly establish whether it is the aquifer or the borehole that is failing as discussed by Robins, Davies and Farr (2012) when considering Malawi data.

A weak link in all the small town water supply management and sustainability is the chronic non-payment of water charges by state and parastatal institutions: Schools, clinics and advisory offices are almost universally in default: although with political risks this can be addressed as seen in Kenya.

Ensuring the sustainability of small-town water supplies where the schemes have only one abstraction borehole raises the issue of covering pump breakdowns. If an interim replacement of existing hand-pumps with small submersible pumps had been undertaken, they would provide some form of system backup (Box 7). All management models rely on sufficient trained staffing and funds plus a robust supply chain. To avoid continuing weakness in all these areas, pumping equipment suppliers should be encouraged to offer alternative long-term leasing agreements, covering maintenance and replacement of the borehole pumps and control equipment.

10. Prospects for Regulating Energy Efficiency and Smarter 'Skimming' in Thin Aquifers

For the large urban, industrial and irrigation users, the major manufacturers will continue to develop more efficient pumps and control systems. The main areas for technical improvement focus on optimizing pumping efficiency by balancing the discharge pressure and yield to match the required operating performance. With installed pumps usually over-specified in terms of both pumping head capacity and discharge, throttling back the yield has been achieved by partially closing a control valve to choke off the flow. With rotodynamic pumps, this increases the system hydraulic losses and decreases the pumping efficiency. While this method is still widely used, a more efficient reduction of yield is achieved by fitting a bypass valve that allows part of the pumped flow to be returned down the borehole. This achieves the desired drop in yield without increasing the hydraulic losses. Both methods have been widely used to control groundwater irrigation pumping.



PWM =
Pulse width modulation (modifies AC frequency wave form by rapid on-off switching: also known as pulsed duration modulation)

PAM =
Pulse amplitude modulation

Figure 16: Variable speed drive (VSD) options and generic electric motors (redrawn from Hydraulic Institute, Europump and US Department of Energy, 2004).

The introduction of mechanical and electronic variable speed devices provides a more efficient method to control both the head and yield performance of diesel and electrically powered rotodynamic pumps. They also can be used for positive-displacement pumps as shown on Figure 16. The use of shaft-driven progress-cavity VSD pumps coupled to pressure transducers could provide the necessary steady-state drawdown conditions to control the movement of saline interfaces and for the skimming of thin aquifers.

Trails combining the two main forms of renewable energy, wind generators and solar power with VSD pumps should enhance the capacity and performance of these systems.

It is envisaged that the advances derived from the manufacturers' research and developments will be adapted by the globalization of the pump manufacture to benefit the lower end of the market. This should lead to pumps incorporating smart speed controls, and wear monitoring sensors becoming widely available. Apart from offering considerable energy savings, VSD motor technology should encourage continuous steady operation of submersible pumps for both small town water supplies and small-scale low-pressure irrigation applications. With the submersible pumps operating at controlled and reduced loads will also extend the life of the pump and motor bearings. This will also reduce the additional start-up and stopping loads that can shorten motor life. Most economic analyses show the VSD technology to be cost effective.

The further efficiency gains from continuous groundwater pumping at a reduced rate are: lower well losses associated with the lower entrance velocity; lower pumping heads; and a decrease in the flow-back disturbance at the natural or artificial gravel pack well screen-aquifer interface.

11. Toward Convergence of Technology, Sustainable Use and Emissions Reduction

Whether the scope, forms and settings for governance exist at the point of groundwater abstraction has to be examined from the point of view of the main stakeholders – regulators, users and suppliers. But regulation of groundwater abstraction is usually confounded by being asked to encourage access and volume on one hand, while also judging when use becomes 'unsustainable'. For instance the universally adopted Millennium Declaration to protect the common environment specifically charges regulators: "to stop the unsustainable exploitation of water resources by developing water management strategies at the regional, national and local levels, which promote both equitable access and adequate supplies".

However, under inherited colonial legislation or deliberate policies, the regulators have been left with the intractable common-law-based rule of capture that still gives full groundwater use rights to landowners. This *de facto* private ownership and development of groundwater will continue to attract state-of-the-art drilling and pumping technology with the narrow objective of private profit without reference to the common good objectives of modern resourced governance.

11.1 Re-writing or delegating the legislative framework

Establishing the appropriate level for defining and enforcing a legislative framework appears to show that the strongest and most effective governance regimes are based on community management groups. In the drier States of Texas and New Mexico, USA, the rule of capture remains in force but the responsibilities to a virtual full adherence to the Millennium Declaration are forced on to the GMDs. Looking at the responsibilities placed on GMDs in Texas, USA shows that the role of governance on groundwater abstraction for irrigation is the same whether declared at the State, national or district level and cannot be convincingly separated. However, it appears logical to assume that the more local the governance decisions are made the more readily they are enforceable and revised as circumstances demand. For example, while the Texas State Legislature can maintain they are adhering to the declaration of property rights under the USA Constitution, in practice they are delegating the derogation of these rights down to the GMD level. In many cases, these GMDs go further than the neighbouring states using the prior appropriation doctrine to water rights and, based on the "50% rule", can include the Texan GMDs dictating the size of pumps that a landowner can install and revising groundwater rights downwards to curb over-abstraction. It is noteworthy that Texan landowners are not automatically permitted to export abstracted groundwater off their lands. This contrasts with India where the rule of capture remains an unchallenged, inalienable right and landowners can profit from the sale of groundwater. This has given rise to a private water market.

Further examples of users attempting to control groundwater use within their own sphere of influence are described by van Steenbergen and Shah (IWMI, 2007b). These initiatives are almost always prompted by one of three factors – declining groundwater levels, declining yields or saline intrusion – or by all three. Most self-management examples are based on community or groundwater user committees that concentrate on collective exploitation of the resource and apply restrictions on individual users and on the construction of new wells. This approach carries cost implications and, as farming and landownership patterns change over time, the community management systems are found to be unstable and break down. In many cases, the impact of outside influences and developments such as a more centralized and subsidized provision of irrigation water will accelerate the decline in what were previously workable solutions. In Mexico, more formal groundwater committees have been given responsibilities similar to those covered by the GMD legislation in Texas. Superficially many of these local initiatives mirror the traditional practices as set out in the "Alghani".

11.2 Reappraising the culture of subsidies

The regional contrasts in the application of subsidies are also instructive. Across Africa, much of the colonial water resource legislation was aimed at promoting economic growth. Annual development budgets included a variety of grants, rebates and subsidies for the borehole drilling for private individuals (e.g. Zambian DWID Report of 1953). From the late 1960s, the Asian green revolution has seen a much more extensive use of subsidies for groundwater irrigation to achieve food self-sufficiency and improve rural livelihoods.

Some subsidises are directly tied to groundwater abstraction and some indirectly impact on the pattern of irrigation. The direct subsidies cover the drilling of tube wells, provision of pumps and fixing energy costs. The indirect subsidies cover inputs – seeds and fertilizer – and outputs – largely guaranteed crop prices. They also can include tax breaks on capital investment and, more questionably, attempts to claim a groundwater depletion rebate in some States in the USA.

Often initially justifiable, subsidies have frequently become multi-layered and indiscriminately applied to the extent that they can become counterproductive from the point of view of both the user and resource. The rural de-electrification across the eastern Indian States required the introduction of the diesel pump subsidies and now the irrigators are pushing for subsidized fuel or a free allowance. The steep worldwide rise in grain prices has seen simple cultivation subsidies in Nebraska, USA, of some USD 500 per hectare purely adding to the already high profit margins achieved during the currently reactivated speculative groundwater irrigation market.

Essentially the use of direct subsidies to groundwater irrigation largely undermines the legislators' ability to control the resource usage unless they are prepared to take the potentially politically damaging decisions to realign the system at a later stage. There is often strong social resistance to the inevitable readjustment or withdrawal of any subsidy. The Gujarat *Jyotirgram* scheme, however, does show that such adjustments can be made if there are positive outcomes for the users. Across Peninsular India, on the other hand, attempts to replay the rural de-electrification through neglect may prove politically difficult or more likely, politically unacceptable.

11.3 Equitable redistribution and sharing of the resource

A further area that requires legislative oversight is the resource governance attached to the long term leasing of State or requisitioned community lands for agricultural development to foreign sovereign or international speculative funds. If groundwater is accepted as a common good, such requisitions have to be assessed on a user-motive basis rather than solely on a profit motive. In many cases, investments are likely to prove to be short term and environmentally damaging and, in the long term, are likely to have lasting adverse economic impacts on indigenous farmers or pastoralists. The Nebraskan Sandhills speculative developments (See Section 6.4) suggest a likely growth in social resistance.

The core of groundwater science and legislation evolved from conflicts that arose from the practice known in the early oilfield developments as "offsetting" when a landowner drilled a successful oil well near his property boundary, his neighbour responded by drilling another oil well on his own property as close as possible to the successful well. As a result, the effective doubling of the oil abstraction impacted on the yield of the first well. In the USA, where a producing oilfield was controlled by several oilfield companies or land owners, the oil-well operators rapidly became aware of the damage that well offsetting did to the reservoir and the resulting reduction in their collective oil recovery. This was predominately caused by the up-coning of saline formation water from below that broke up the continuity of the oil layer. In response to this problem the oil operators adopted a control model based on the concept of resource unitization where each operator received a prior agreed quota of the overall field production.

The practice of offsetting was repeated by groundwater irrigators and was dealt with in the first revision of the Nebraska groundwater legislation, passed in 1957. This was based on the view that groundwater was a common-pooled resource and the legislation included the registration of irrigation wells and placed a minimum 200 m well spacing. The subtle difference between the unitization development model and the common-pooled resource is that the unitization model is centred on managing the *in-situ* pore fluids to maximize their recovery for the benefit of all developers, whereas the common-pooled model concentrates on the distribution of groundwater abstraction rights. The basic features of the resource unitization model compared to the common-pooled resource model are shown on Table 10.

While there are no published examples of unitization being used to regulate groundwater abstraction, Jarvis, 2011, reports that the principles are being applied in Utah, USA, where landowners, facing a State-enforced reduction in groundwater abstraction, voluntarily pooled their groundwater abstraction rights and formed a "unit" – the Escalante Valley Water Users Association – to share the reduction in available groundwater. A similar scheme was also initiated in the over-stressed groundwater basins of the Milford Flat area in western Utah.

Table 10: Design attributes and principles of unitization versus common-pool resources (from Jarvis, 2011).

Principle or attribute	Unitization	Common-pool resources
Conceptual development	1890–1930s	1960–90s
Boundaries	• Voluntary units • Compulsory/conservation units • Geographic units • Geologic units	Clearly define boundaries for the user pool and the resource domain
Rules	• Pre-unit agreements at appraisal • Unitization agreement at pre-development • Redetermination during development	Appropriation rules developed for local conditions and provisional rules developed for resource maintenance
Collective action	• Collectively beneficial • Allows sharing of development infrastructure • Avoids unnecessary wells and infrastructure occurring under the competitive rule of capture	Collective-choice arrangements developed by the resource users
Monitoring	• Uses pressure maintenance on the reservoir • Uses best technical or engineering information • Provides foundation to carry out a secondary recovery programme	Monitoring programmes developed for the resource
Sanctions	• Gives all owners of rights in the common reservoir a fair share of the production	Graduated sanctions developed for “violators” of the rules
Dispute resolution	• Pre-unit agreement • Industry-standard agreements • Redetermination process	Conflict-management schemes developed
Rights of regimes	• Can be developed through voluntary or government-mandated compulsory action	Rights of organized environmental regimes respected by external authorities
Administration	• Voluntary to compulsory • Other alternatives (for example, sole development, partitioned development, fixed equity, buy-out, or asset swaps)	Nested enterprises used to administer management

In areas where many landholdings are less than a hectare, interference between water wells is unavoidable, and in most cases, when more efficient pumps became available, many productive wells dried up as the cones of depression from the deeper wells dewatered the unconfined aquifers. While the prior appropriation doctrine governing water rights specifically targeted this problem, the adoption of effective solutions requires a good understanding of the resources available. In areas of deliberate groundwater over-abstraction, it has been found that water rights assigned under the prior appropriation doctrine need to be periodically adjusted to maintain the equitable allocation of the resource.

In the near future, there will be the need to address the governance of the public and private groundwater markets as they are very open to abuse. Close monitoring and auditing will be required to ensure that no entrenched monopolies develop and that profit margins are not exploitative. In the long run, however, groundwater markets could prove socially unstable and divisive, unless a new governance model is developed along the unitization development lines, as suggested by Jarvis (2011), where the benefits of the resource are jointly shared.

Beyond equitable sharing of the resource, users are entitled to rely on the durability and efficiency of their pumping equipment. This should be protected by government legislation and/or industrial standards. Users also require secure access to electricity supplies or fuel and to spare parts and repair facilities. Achieving these objectives requires the attention of national regulatory bodies, as well as strong political will. The regulation and governance of pump manufacturers and suppliers is generally tied directly to industry organizations operating to and within government guidelines, as seen in the role of Europump in advising its members on compliance with the EU directives. These guidelines and regulations cover all aspects of manufactured goods, including materials, construction, efficiency and safety aspects.

The nuances of local governance in communally-owned or -managed groundwater abstraction systems have been widely analysed and solutions adopted as the result of collective community decision are seen as sound. However, several minor problems occur, particularly where small diesel-powered pumps are collectively shared amongst several users who tend to sidestep equipment maintenance. Wider adoption of equitable groundwater rights legislation will be central to realigning the role of groundwater irrigation abstraction into the future. Maintaining social cohesion will drive this need and highlight the urgency for action.

Where the distribution and quality of groundwater data and the level of understanding of the resource is weak, assigned-priority water rights legislation as applied in Wyoming, USA, is an appropriate default model (see section 5.4). Applying this doctrine to motor-powered pumping rights will give drinking water for humans and animals the highest priority followed by municipal supplies. It also categorizes irrigation as a non-preferred use. Having stood the test of time, all hand- and animal-drawn water can be exempt from control. This will encourage the application of low technological solutions to rural water supplies and small-scale irrigation and can be extended to all groundwater developments, irrespective of the uses, through the implementation of the incrementally stepped development model (Box 7) developed by the 1970's World Bank Technology Advisory Group (Sounders and Warford, 1976).

If donors and funding agents follow this approach, the new rural water supplies will be more widely and evenly spread. This will remove one of the complaints about the selective nature of existing development programmes. It is also more suitable for the execution under the decentralization plans with limited trained manpower, given that skills and training can evolve as the level of technology applied also advances incrementally.

11.4 Future technological developments

The trends in the adoption of more precise and energy-efficient pumping technologies indicate that the global stock of groundwater pumping mechanisms can be expected to expand but that the structure will remain constant. Low-lift and low-output devices will still be needed and will service low-intensity abstractions. However, the adoption of higher capacity and higher reliability technology for high-value productive uses, including municipal water supply, industry and agriculture is likely to further concentrate intensive abstraction from aquifers that are already at risk.

Unless restricted by external controls, past experience has demonstrated that any efficiency gains achieved in groundwater pumping for irrigation are usually taken up by an expansion of the cultivated area that is likely to be coupled with negative groundwater trends. In addition, where externally-funded large-scale groundwater irrigation projects are implemented in traditional groundwater irrigation communities, they can often lead to seasonal gluts of agricultural produce that depress the local prices unless steps are taken to widen the marketing area or to feed a local food-processing sector.

Searching for future technological advances in pumping technology shows the practical uses of two materials are set to be the focus of long term electrical developments, usage and loss reduction: these are superconductors and graphene. At room temperature the normal electrical resistance losses are at least 20 percent. Initially, superconductors required cooling metals to close to zero degrees Kelvin (-273,15^0 C). Currently superconductors that work at around 70^0 Kelvin (-203,15^0 C) are available. This temperature is 7^0 Kelvin less than the boiling point of liquid nitrogen (77^0 K). Samples of superconductive material generate very strong magnetic fields, so if commercially-produced superconductor materials are developed, electric motors will be smaller, more efficient and more powerful[13].

Further approaches to superconductivity research include experiments with low-resistance, graphene nanotubes, but the main graphene applications of immediate interest are graphene photovoltaics that promise to provide a much cheaper solution to solar power generation. Other developments already in use are the super capacitors to replace batteries for electrical storage. Currently their storage capacity is only around 50 percent of that of batteries but they can be recharged in a matter of minutes and have a recycling efficiency of over 95 percent. Future developments in this field are likely to find wide application in the storage of solar and wind power. The super capacitors are already in pilot use for electric trains and trams in China.

[13] The enhanced magnetic properties of superconductors (the Meissner effect) could be used to provide highly efficient magnetic energy storage. In 2011, a number of researchers claimed to have achieved superconductivity in complex copper compounds at room temperature and if successful such enhanced electro-magnetic properties will enable pump motors to run cooler and lower the inherent energy losses associated with the rotor-stator gap. Higher rotation speeds will also be possible and enable higher vane tip velocities to be achieved in smaller diameter impellers. The vane tip velocity controls the available pumping head. Currently the maximum head for a single impeller rotodynamic pump is around 1 000m.

12. Conclusions

Within the remit, namely, "*Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction",* a consistent pattern is identified where early in the development cycle, the rapid and unrestrained take up of all advances in pumping technology has led to the overexploitation of the resource base. This in turn has prompted governments to introduce legislation to regulate groundwater abstraction. However, these initiatives have been constrained by an imperfect understanding of the groundwater occurrences.

Prior to the middle of the 19th century, the low intensity of groundwater abstraction had marginal impact on the groundwater resources and, as abstraction points were constructed and owned by individuals or communities, their rights to the groundwater were largely guaranteed by common law.

However, advances in groundwater pumping technology from the mid-19th century that helped underpin worldwide population and economic growth soon began to have unforeseen consequences. By 1900, declining groundwater levels were driving up pumping costs and reducing surface water stream flows. Investigation of these problems formed the focus of early hydrogeological studies while parallel studies of the potent health risks from groundwater contamination resulted in the introduction of the first groundwater legislation.

Within the spectrum of groundwater uses, technology has provided a continuously improving choice of more powerful and efficient pumps and the development of shaft turbine and submersible pumps throughout the 20th century supported the worldwide growth of groundwater-based irrigation. Initially, and in places still unregulated, this irrigation abstraction has been mainly responsible for the most heavily depleted aquifers. The necessary legislation to control overdevelopment of the resource has arguably lagged behind the rate of depletion.

The requirements of abstraction well owners are the security, reliability and economics of their groundwater supply: where security covers rights to abstract, the sustainability of the resource in terms of quantity and quality; reliability covers the robustness of the pumping equipment and power source and; economics includes the capital investment, operation and maintenance costs.

Meeting these pump owners' requirements shows the role for governments is to establish sound water rights legislation to ensure the sustainability of the groundwater supply and to set minimum efficiency and quality standards for the pump manufacturers and to ensure ready access to appropriate energy supplies. While governments have a lesser role in the economics of pumping as this should be dictated by market forces, they are seen to be considerably distorted for political purposes by a variety of subsidies.

A further important role for governments is encouraging research and innovation not just to regulate patterns of intensive abstraction for the common good but also to ensure equal access to the technology advances to the benefit all users. This is particular applicable to ensuring more efficient water usage in the irrigation sector. The research includes not only into mapping and quantifying the available groundwater resources but equally important to sound governance of groundwater abstraction is the requirement for constant monitoring of the groundwater abstraction, levels and quality.

On the legislative side, the unanimous adoption by the 193 UN member countries of the 2000 Millennium Declaration on the environment has marked a turning point as both national and international attitudes recognized the need for compliance and for realignment and enforcement of groundwater resources management, which can only be achieved by the introduction of equitable water rights. However, implementation of legislation covering groundwater abstraction for irrigation has proven, and will still prove, particularly problematic as in many countries the political emphasis still remains on trying to meet farming community demands for a secure supply of groundwater from a continually declining resource.

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Macro-economic Trends that Influence Demand for Groundwater and Related Services

Digest

Relevance

A macro-economic treatment of groundwater is elusive even when it is the primary source of productive water in national economies. Perceptions about the utility of groundwater and related aquifer services are conditioned more by micro-economic transactions – private preferences to develop groundwater (and the ease of disposal to aquifers) than common understanding of a shared vulnerable resource. Simply adding some conceptual clarity on basic economic variables such as prices, values, costs and benefits in relation to groundwater has proved difficult. This difficulty has roots in the hidden nature of the resource but it is also hard to account for and track use when the resource and its users are highly distributed and when the change in and out of surface and subsurface stores is rapid – as in the case of large alluvial valleys where groundwater is intensively pumped.

The implications for groundwater governance are manifold. The macro-economic conditions under which many private decisions to pump groundwater or pollute aquifers are taken may have little impact where (and when) demand is inelastic because there is no alternative source or a means of disposal. And while agricultural groundwater supply may be highly elastic with respect to commodity price signals, evidence points to highly inelastic demand for groundwater when input subsidies for energy are removed or fuel taxes imposed.

The economic roles of groundwater

The aggregate economic contribution of groundwater to economic development of a particular national economy has been estimated in only a few cases. For instance the Planning Commission for India has estimated that groundwater makes a 9 % contribution to GDP. Even then this may be an under-estimate if only agricultural production is factored in and not the array of urban and municipal services derived from India's aquifers. However, the formal macro-economic treatment of water, let alone groundwater, in computable general equilibrium (CGE) models is limited. While partial equilibrium analysis in specific economic sectors, notably agriculture, have been more widely applied, the problem of linking natural systems of groundwater circulation to an aggregated economic model of national accounts remains.

For economies with both surface and groundwater resources, the economic perception of groundwater value is limited at macro level where economists have difficulty accounting for a resource that does not have clear boundary conditions (hard to treat as a 'stock' in conventional resource accounting). Even when accounted for, the value added through water derived from aquifers may be small in comparison to other inputs for managing water and adding value (energy, labour, seed, fertilizer, etc)

In economies with no alternative freshwater supply, planned depletion of non-renewable groundwater stocks has become standard practice on the assumption that economic wealth creation from that stock generates a set of economic substitutes that will maintain rates of economic growth.

The most common economic instruments used in groundwater management have been:

- Changing groundwater abstraction/pollution costs either through direct pricing with resource abstraction/pollution fees; indirect pricing via increasing energy tariffs or the introduction of water use right markets.
- Positive economic incentives for certain abstraction and pollution activities by changes to agriculture and food trade policies.
- Subsidies for 'efficient' irrigation.

But economic instruments designed to lower water abstraction levels may lead to paradoxical outcomes. Using less water per crop does not necessarily mean using less water overall (at a plot, farm, irrigation district or basin level).

Constraints

The nature of groundwater poses specific challenges to the implementation of economic policy instruments: the relatively high cost and complexity of assessing these resources, the highly decentralized resource use which increases management monitoring costs, the invisibility of groundwater to the general public, varying impacts of contaminant load depending on aquifer vulnerability, long-time lags and the near irreversibility of most aquifer contamination. In addition the limited perception of current groundwater values and inter-generational values can be expected to place a drag on the creation of a good governance environment.

For instance, the levels of macro-economic risk posed by extreme weather and climate events have become more apparent as competition for scarce water resources has intensified and the vulnerability to flood events has grown as populations have concentrated and grown. However, even if these events pierce the public conscience, the role of groundwater as a buffer and moderator is largely ignored with a general preference to emphasize groundwater 'potential' rather than groundwater limits set by patterns of depletion and pollution. The social costs of this ignorance rarely appear as 'shocks' or contingent liabilities on national budgets. Equally the benefits of the specific value added to national welfare or foreign exchange earnings can be difficult to untangle from surface water unless the economy is entirely dependent upon groundwater. If factoring water generally in macro-economic accounts has proved difficult or controversial, then the task is even more challenging for groundwater.

Prospects

The disposition of aquifers, the nature of groundwater circulation and the styles and patterns of use should make cooperation schemes especially appealing for promoting groundwater governance and implementing management. Cooperation, instead of competition, between water users can help preserve water resources, conserve assets and share benefits thus obtained (i.e. voluntary agreements, including payment for environmental services).

As economists move from standard measures of productivity (GDP) to total factor productivity (TFP) and methods of natural resource accounting, the instrumental value of groundwater over time can be expected to become more explicit. However, for many of the prime aquifers in the earth's crust, this revelation will be too late to avoid outright depletion or loss of hydrogeological integrity.

What should be possible is at least a slowing down of depletion and degradation trends through more enlightened economic policy incentives that encourage informed, responsible use of groundwater. Incentives for local government to implement natural resource management agreements with user groups could be one avenue if married with removal of subsidy regimes that encouraged concentration of agro-chemical inputs, for instance.

Conclusions and messages

Dependable public information on the state of local groundwater resources would appear to be critical. At micro-economic level (the level of the household or business) dependency may be very high, but low levels of understanding of groundwater and aquifer processes limit prospects for expanding or reinforcing systems of local governance around the aquifer systems that matter – and at the scales for which economic policy is formulated.

Refinement of groundwater accounting will help, but instances of explicit groundwater accounting are limited, and the results in terms of local governance are mixed even when local institutions are strong and regulation of water resources in the public interest is widely accepted.

Finally, cooperation and voluntary agreements may not only be a possibility but rather a logical need. However if economic incentives to enable those cooperative schemes are not evident, they may not work.

Governance of the Subsurface Space and Groundwater Frontiers

Digest

Subsurface space and groundwater frontiers: their relevance for groundwater governance

Use of the subsurface has become steadily more intensive and globalized, both by the intensification of conventional uses of the subsurface and its resources, and by the emergence of relatively new, non-conventional uses. The first category includes groundwater abstraction and the extraction of minerals and hydrocarbons. Using the subsurface for developing geothermal energy, for systematic disposal of hazardous waste or for various injection/recovery applications in permeable geologic formations, or through hydrofracturing of impervious ones, started more recently. Subsurface construction may be a conventional activity, but its expansion in urban areas and transport corridors is unprecedented and often not well coordinated. Likewise, groundwater abstraction is in some areas shifting to aquifers at greater depths than ever before.

These human subsurface activities interact and their interactions increase with the number and intensity of the activities. Groundwater systems play a crucial role because they are easily affected by a wide range of subsurface activities, while the relatively mobile groundwater acts as an agent to transfer the impulses and effects quickly throughout hydraulically connected aquifers and related surface water bodies. While the enhanced sustainable use of the subsurface should be pursued and encouraged, effective governance in particular of groundwater is needed to manage these interactions or mitigate the negative impacts that they may produce.

Main activities under the theme and their geographic distribution

A diversity of activities resort under the theme 'subsurface space and groundwater frontiers'. Table 1 provides an overview.

Table 1 Principal human subsurface activity

Category	Type of activity	Geographic distribution
1. Pushing the aquifer frontier	Groundwater withdrawal from deep-seated aquifers (approximately beyond 500 m deep)	Still limited. Potential exists in areas where deep sedimentary basins occur in combination with poor shallow aquifers.
2. Mining	Extraction of minerals	In zones where profitable mineral resources have been identified (scattered over the globe).
3. Subsurface energy development	Oil and gas development	In zones where profitable hydrocarbon resources have been identified (in major geological basins on- and off-shore).
	High-enthalpy geothermal energy development	Areas of favourable temperature anomalies (e.g. in USA, Japan, Iceland, Italy, Central America, Indonesia, Philippines, Kenya, China (Tibet), etc.)
	Low-enthalpy geothermal resources development	Major sedimentary basins (e.g. in France, Germany, Brazil, etc.)

Category	Type of activity	Geographic distribution
4. Disposal and storage of hazardous wastes	Disposal by deep well injection	Often associated with mining, or with oil and gas industry
	Subsurface storage of radioactive waste	Most of it in selected countries, e.g. USA, France, Russia, Japan and India
	Nuclear weapons testing and nuclear power accidents	E.g. in Western USA and French Polynesia (tests); Russia and Japan (accidents)
5. Injection and recovery	Solution mining (e.g. using acids and other lixiviants)	In selected mining areas
	Reservoir management by injecting residual geothermal fluids	In geothermal energy development areas
	Storage of hydrocarbons and fluids associated with oil and natural gas production	In or near oil and gas production areas
	Hydraulic fracturing or 'fracking'	In zones where shale gas is exploited
	Carbon capture and sequestration	Major projects in North Sea, in Canada and in Algeria.
6. Construction into underground space	Pipelines, sewerage systems and cables	Very general around the world, in particular in developed countries
	Tunnels and underground railways	In particular in many urban centres around the world.
	Underground car parks and other underground constructions	In particular in urban areas in industria-lised countries where space is scarce.

What is known about the issues and constraints?

A high level of technical expertise has been applied to all activities mentioned in Table 1. Often the expertise does more than focus on the immediate purpose of these activities (such as how to exploit a specific resource) and enables assessing the associated risks, constraints and the direct impacts on other activities or interests (economic externalities) or contributes to mitigating the latter. In some cases technical expertise is directed toward broader governance of the subsurface domain as systems of safety and environmental compliance are put in place by the industries and their regulators.

Technological knowledge related to the activities rests with specialised companies or organisations and is subject to continuous innovation. In spite of numerous time-consuming and expensive exploration and assessment efforts, knowledge of the properties and behaviour of the subsurface remains often the largest source of uncertainty.

To complicate the governance challenge, these risks and externalities are often inseparable. The most commonly recognised ones are:

- Subsidence or collapse of the land surface due to the subsurface removal of solids or fluids, causing damage to constructions, pipelines, etc.
- Well blow-outs and oil spills.

- Health risks if subsurface storage would fail to isolate hazardous waste (in particular radioactive waste) or other hazardous substances (e.g. carbon dioxide) from the human environment (including flora and fauna at or near land surface).
- Degradation of groundwater resources by uncontrolled depletion or pollution.
- Negative impacts on local hydrological regimes and ecosystems.

In addition to constraints to developing a single technical subsurface activity, there are practical constraints to achieving 'good governance' of the underground space. Among them, the following ones are most important:

- Fragmentation of mandates and legislation related to subsurface activities.
- Insufficient capacity, mandate and funds of the institutions in charge of governance.
- Inadequate or poorly informed legislation and regulatory frameworks.
- Insufficient political support, vision and/or power.
- Relevant stakeholders not or poorly involved (leading – among others – to lack of confidence and to public opposition to activities that are expected to have health risks or to cause damage to private property or the environment).
- Insufficient and/or unreliable information on the local factual situation, the predicted futures and the associated benefits, costs, risks and external impacts.

Several of these constraints to governance can be observed in most countries.

What decision-makers and engaged stakeholders need to know

Decision-makers and stakeholders involved in decision-making processes on the use of the subsurface need to be aware both of the many potential and current uses of the subsurface and its resources in the area of their concern, and of the geological characteristics of the area's subsurface. Furthermore, they need to have a reliable picture of the benefits, costs and risks of the individual subsurface activities (in comparison with those of non-subsurface alternatives), but they need also to understand that the different uses may interfere and produce externalities.

In addition, there are two more key lessons to learn about the subsurface domain. First, that it is difficult and expensive to explore the subsurface adequately, which results in practice in large uncertainties on the assumed properties and potential of the underground. Second, that many processes that produce change in the subsurface are virtually irreversible, on a human time scale – or reversible only at a very high cost.

Therefore those responsible for groundwater resources management should be involved in the decision-making process on any new subsurface project and should make sure that all new initiatives for subsurface activities are known to them in time. They should also make sure that sufficient efforts are made to assess external risks and other external impacts, that regulations exist to promote orderly behaviour, that all projects comply with these regulations and that they follow carefully what changes over time in the subsurface and related environment do occur. This is important as efforts to mitigate and manage risks may only have a small window of opportunity to be effective and prevent the irreversible change indicated above.

Key prospects and recommendations

General

Technology is expected to play a major role in the future of governing the subsurface. Technological innovation will enhance technical capabilities and reduce costs and risks, with the result that uses of subsurface space and resources will become more diverse and more intensive. This will require an improved groundwater and subsurface governance: more integrated, more pro-active, smarter regulations and better co-operation between all parties involved.

The lack of factual information and knowledge on the subsurface will remain a severe constraint to groundwater governance. In many countries government bodies, groundwater users associations, academia, professional organisations and international organisations are making significant steps towards sharing their information and knowledge. However, platforms for joining forces in a similar way between the public and the private sector are, for the most part, absent. Within the private sector, in particular the mining and energy industry, there is a wealth of information on the deeper parts of the subsurface that is still relevant for groundwater development and management; therefore, a general recommendation is to explore options and modalities for establishing private-public cooperation in this field.

The aspiration of regulating the underground space will challenge geologists and other professionals to play new roles in the future: including the role of well-informed advisors in defining policies and strategies for the utilization of subsurface space and resources. For this role, they may need to acquire a broad and multidisciplinary vision – rooted in natural and social science alike.

Planning the different categories of activities related to the subsurface is in most countries extremely fragmented and uncoordinated. Trends towards integrated management of the use of the subsurface and its resources can be observed in some countries. This integration needs to be an over-arching general recommendation intended to avoid, mitigate and manage the risks of entering the subsurface domain, while taking full advantage of the many opportunities that the subsurface space and subsurface resources may provide.

Activity-specific

Deep-seated aquifers so far are only sparsely tapped around the world, but it is expected that they will be exploited with increasing intensity for vital freshwater supplies. They may also gain importance in the near future as a source for emergency supplies and as a buffer to mitigate climate change impacts. A considerable part of these confined water resources is however effectively non-renewable, being totally or largely de-coupled from contemporary recharge. While there is no global consensus on how to exploit non-renewable freshwater resources for optimal societal benefit, the 'managed' exploitation of these resources is ongoing in a number of arid or semi-arid nations, where they play a crucial role in sustaining lives and livelihoods. Depending on depth, such resources may come under different legislation and institutional mandates compared with shallow more accessible aquifers (mining *versus* water resources).

Mining and hydrocarbon activities produce enormous economic benefits around the world, but the impact of mineral and hydrocarbon recovery pose considerable risks to groundwater resources and the environment. Countries with weak legislation and enforcement capabilities are likely to be faced with a growing legacy of resource and environmental problems.

Global use of geothermal energy is annually growing at a rate of 14%, but it still remains an underdeveloped energy resource, compared to the vast amount of thermal energy stored within the Earth's crust. Access to this huge, low cost, clean energy resource that could be considered infinite on a human time scale, is possible, but requires a number of technical and financial constraints to be overcome.

The subsurface is progressively more being used for storage of hazardous waste such as nuclear waste and other liquid or solid wastes. Related activities (often using similar techniques such as injection wells) are the injection of fluids for soluble mineral extraction, the storage and recovery of heat and hydrocarbons, carbon capture and sequestration (CCS), hydraulic fracturing ('fracking') and the injection of residual geothermal fluids. All these activities lead to pollution of the subsurface, in some cases with exotic substances, many of which may be harmful or even dangerous. Strict adherence to adequate regulations therefore is necessary to protect the subsurface environment and related resources. Such regulations exist and are imposed in some countries, while in other countries they are absent, insufficient or not enforced at all. Strong public opposition (by action groups) is sometimes observed against some types of hazardous waste disposal, especially related to nuclear waste disposal and to CCS, usually because the government is not transparent or there is no confidence in the government's risk assessment and/or the quality of the intended protecting measures. Integrated governance is required here and should pay due attention to stakeholder involvement.

Use of the subsurface space for underground pipelines, cables, car parks, buildings and other technical infrastructure is rapidly increasing. Regulations on such underground construction activities do exist in many countries, but fall generally under different jurisdictions and compliance may be weak in many cases. The subject is rarely included in regular groundwater management plans.

Thematic Paper 10

GOVERNANCE OF THE SUBSURFACE SPACE AND GROUNDWATER FRONTIERS

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Acronyms

CCS – Carbon Capture and Sequestration

EGS – Enhanced Geothermal System

E&P – Exploration and Production

EU – European Union

GPS – Global Positioning System

HDR – Hot Dry Rock

HSA – Hot Sedimentary Aquifer

HWR – Hot Wet Rock

IDDP – Iceland Deep Drilling Project

NGO – Non-Governmental Organization

SADC – Southern African Development Community

SGS – Supercritical Geothermal System

UK – United Kingdom

USA – United States of America

US EPA – United States Environmental Protection Agency

1. Introduction

This thematic paper focuses on the conventional and non-conventional use of aquifers, encroachment into the subsurface space and the evolution of groundwater 'frontiers' to the extent that they impact aquifers and pose new challenges for groundwater governance. Some uses of the underground space, such as mining, are not new, but the scale and intensity of mining activity and the environmental consequence of groundwater recovery in abandoned mines are such that groundwater legislation has to 'catch up'[1]. The same applies to the controversial use of hydrofracturing (or 'fracking') to capture shale gas. The technological limits to mankind's interference with the Earth's crust are important considerations and Box 2 indicates where the current limits stand.
For reference, the working definition of groundwater governance adopted by the project is given in Box 1.

Box 1: A working definition of groundwater governance

Groundwater governance is the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck. 2007. Dictionary and Introduction to Global Environmental Governance)

Groundwater protection forms the main governance concern when abstracting water, gas and oil resources and when using wells to inject fluids into underground formations. These developments have always been expensive ventures: expensive, originally in terms of manpower, and latterly, in terms of finance. However, in the past the detrimental environmental impacts were not usually understood both during operation and subsequently after abandonment. As a result there is a growing legacy of environmental problems to be addressed. The 10 000 m^3/day Sidoarjo mud flow (Lusi) from a gas exploration well that went wrong in Eastern Java is a classic example: unstemmed, the Sidoarjo flow is expected to last more than 30 years by which time some 0.11 km^3 of mud will be expelled and flood the surrounding heavily populated area.

Since geology is essential for technically assessing groundwater frontiers and the subsurface space, the paper first focuses on the geological setting of deeper aquifers and sedimentary formations. The geological history of a formation dictates its water-bearing characteristics, both in terms of porosity and permeability. It also indicates whether the groundwater is part of the current or a recent-past hydrological cycle and whether it is connate (trapped when the formation was deposited) or juvenile (has a deep seated origin). In some cases the base of deep aquifers is marked by impermeable basement; in others, the vertical limits are not yet proved and have to be inferred from geophysical surveys and interpretations.

While an understanding of the groundwater occurrences cannot be directly translated into governance models, it does provide an essential background to developing workable governance models. Formulating a governance structure to cover the subsurface space and groundwater frontiers needs a deeper geological basis than has been entirely necessary for the management and protection of shallower groundwater occurrences, where a hydrogeological terrain or province classification has proved adequate.

The approach taken in this report is to consider the range of cases where the underground space is being used; these include water supply, minerals extraction, energy generation and conservation, and construction in the underground space. In each case, the geographical distribution and geological setting of the resource is established, and a brief timeline is provided covering the resource exploitation and the necessary legislation that arose to control the beneficial or detrimental impacts of the developments.

This paper does not address the ownership of deep underground space and mineral rights nor does it address the legal conflicts between the holders of water rights and the developers of the underground space. This is largely because the legislation on these matters is always evolving or private property rights are overridden by state claims to ownership of mineral rights. For these specific legal issues, reference should be made to Thematic Paper 6.

[1] See Draft New South Wales (Australia) Aquifer Interference Policy (http://www.water.nsw.gov.au/Water-management/Law-and-policy/Legal-reform/Legal-reform#policy).

Box 2: The limits to drilling into the Earth's crust

Groundwater, oil and gas are most efficiently abstracted by wells and the first hand-dug wells are dated to 10 000 BC. The deepest hand dug well (385 m) for water supply purposes was completed in 1858 at Woodingdean in southern England. The first drilled wells were constructed using percussion techniques to extract natural brines for salt production in Sichuan, China around 2 000 years ago. Between the 3rd and the early 19th century (1835), the depth drilled increased from 140 m to over 1000 m. Since then the capacity to mechanically drill deeper boreholes has steadily increased and the current depth record is held by the Kola super-deep, scientific investigation borehole in Russia at 12 262 m. The deepest water wells rarely exceed 1 500 m and currently the deepest oil wells rarely exceed 7 500 m vertically.
Oil and gas wells are the second most wide-scale intrusion into the underground space after water wells.
Since 1950, 2.6 million oil and natural gas exploration and production wells have been drilled in the United States of America (USA): in 2009 there were 363 107 producing oil and 460 261 producing gas wells[2] in number. According to the American Ground Water Trust, the number of domestic water wells in the USA exceeds 15 million and there are over 250 000 public water supply wells: during 2012 some 600 new water wells are drilled each week in the USA.
Extracting groundwater from wells becomes increasingly technically and economically restricted as the pumping head increases. Positive-displacement reciprocating pumps can be used to lift groundwater from considerably more than 1 500 m, yield performance and efficiency limits their economic application for large-scale groundwater abstraction. The head limit for regular commercial 200 mm electric submersible water pumps is 600 to 650 m but high performance 750 kW multistage submersible pumps used in oil wells can handle heads up to 3 700 m.

Part 1 (Baseline) presents an overall description of different types of use of the subsurface (for disposal and storage purposes; and for accommodating technical infrastructural works) and of the two main forms of deep groundwater exploitation: the abstraction of fresh water from deep-seated aquifers and the use of groundwater as a carrier of geothermal energy. For each of these subjects, current governance practices are briefly reviewed. This part of the paper is concluded by some observations on the planning process and aquifer use.

Part 2 (Diagnostics) explores the most relevant constraints to and opportunities for improving governance. In addition, it addresses a few specific issues concerning deep aquifers.

Part 3 (Prospects) looks into the future. In the first place, it explores the future role of technology in managing the underground space, assesses options for joining forces (enhanced public/private sector co-operation) and makes a plea for more active involvement of geologists and hydrogeologists in the debate on and the planning of the multiple uses of the subsurface and its resources. The paper then draws a number of conclusions.

[2] See United States Energy Information Agency website (http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html).

Part 1 Baseline: Current status of knowledge, utilization and management

2. Pushing the Aquifer Frontier

With few exceptions, groundwater abstraction around the world remained at relatively shallow depth until the end of the 19th century, or even much later in some countries. Apart from diverting water from springs, groundwater mostly used to be tapped by dug wells (rarely deeper than 50 to 100 m as water was lifted by human or animal traction) or by infiltration galleries (e.g. qanats or karez – within tens of meters below surface). Technology for deeper abstraction was not yet available and knowledge on the presence of any aquifers beyond the near surface was in most cases non-existent. Significant advances in drilling and pump technology, as well as in subsurface exploration techniques (geophysics) and geological knowledge, have changed the panorama drastically during the 20th century. Deeper aquifers have been discovered, numerous deep wells have been drilled and wells have been equipped with mechanical pumps, often very powerful ones. Arguably, this has precipitated a 'silent revolution' in groundwater development, resulting in an unprecedented intensity of groundwater abstraction, particularly in arid and semi-arid regions. Wells down to several hundreds of metres of depth are common nowadays almost anywhere in the world. However, wells intended for the abstraction of freshwater for consumptive use (domestic, agricultural or industrial water) are rarely deeper than 400 to 500 m. Indeed most economically recoverable groundwater is derived from the shallow groundwater circulation in the Earth's crust at depths between 0 and 300 metres.

Beyond an arbitrary 500 m limit, groundwater tends to become progressively saline or mineralized as deeper groundwater circulation mixes with juvenile and connate groundwater, and the longer residence times allow more constituents to be dissolved from the rock matrix. Also reliable assessments of aquifer properties and water quality become more expensive and technically demanding to obtain. Currently, exploitation of such aquifers is restricted to the recovery of geothermal energy, which is a non-consumptive water use since the abstracted water usually is re-injected. However, as demand for water increases and shallow aquifers are depleted or degraded, these deeper resources have become attractive where high value uses – including urban water supply and horticultural crops – have been able to afford technology and energy to pump from depths of up to 600 m. With this advance of the groundwater frontier in the 20th century, questions over the long term economic and technical sustainability of deep pumping have arisen (Custodio, 2002; Llamas and Custodio, 2003), particularly where deep aquifer systems are not linked to contemporary recharge and where progressive depletion of pressure and storage within the system is a known consequence (Foster and Loucks, 2006).

2.1 Existing knowledge on deep-seated aquifers

Knowledge on deep-seated aquifers around the world is still scarce, fragmented and in most cases lacking the detail required to make a reliable judgement on the suitability of individual deep aquifers for freshwater withdrawal. They are most likely to be selectively found under certain tectonic settings (Zektser and Everett, 2004; Margat, 2008). A significant percentage of the deep-seated aquifers currently identified are categorized non-renewable resources (Foster and Loucks, 2006), while the remaining ones are only weakly recharged. This creates significantly different conditions and risks for aquifer development compared with the annually recharged shallow aquifer systems. The risk of encountering saline groundwater occurrences is higher in deep-seated aquifers where emplacement of paleo-recharge, mineralization and incursion of juvenile waters has characterised the evolution of the deeper groundwater circulation (Van Weert *et al.*, 2009).

The use of tectonic plate settings by the International Association for Engineering Geology and the Environment (IAEG)[3] to define six forms of sedimentary basin is appropriate for considering the potential occurrence of deep aquifers. However, for hydrogeological purposes, according to the IAEG fore and back arc basins can be considered as a separate depositional environment, with the back arc basins being equated with the IAEG intracratonic basin as shown on Table 1. Also the IAEG foreland basin class essentially equates to a late-stage uplifted continental back-arc-basin environment.

[3] http://www.iaeg.info/totalgeology.

Table 1: Tectonic classification of major sedimentary basins (modified from IAEG).

Basin Type	Characteristic sediments	Depositional environments	Model examples
Rift or aulacogen†	Earliest crystalline rocks overlain by thick gravel and sand; younger rocks may include evaporites and limestones. Long-lived sediment-filled grabens. Little deformation.	Rivers and lakes changing to shallow-marine	Cratons, continental rifts
Back arc – Intra-cratonic	Homogeneous quartz-rich sands and limestones, but may include muds, evaporites or coal at certain times. Little deformation.	Mostly shallow-marine with some deltaic	Platform sediments and basins
Passive margin	Quartz-rich sands and limestones passing seaward to muds. Diapirism (salt domes).	Shallow-marine shelf to deeper-marine geosynclines; deltaic	Platform sediments and basins
Trench	Fine sediments overlying ocean-floor basalts. Extensive. Deformed accretionary wedge.	Deep marine	Accretionary prisms
Fore arc (subduction) zone	Varied thick sediments ranging from pelagic through turbidites to alluvial fans, much derived from adjacent orogenic belts. Volcanoclastics common. Deformed accretionary wedge.	Non-marine to deep marine	Accretionary prisms, fold and thrust belts
Foreland	Heterogeneous gravels, sands and muds derived from the orogenic belt and shed on to the continental craton; may be coal-bearing. Relatively stable areas.	Mostly river and mountain front outwash deposits	Foreland basins

†Aulacogen = failed rift

However, wells intended for the abstraction of freshwater (domestic, agricultural or industrial water) are seldom deeper than 600 m. The scarce available information suggests that freshwater aquifers deeper than 600 m – the so-called 'deep-seated aquifers'[4] – remain largely untapped for the water supply uses.
The sparseness of the available information suggests a governance deficit in respect of the data collection, storage and dissemination. The indications are that considerable groundwater data collected during the 1960s and 1970s was not made widely available even within the commissioning organizations and ministries. The Groundwater Grey Literature Archive of the Southern African Development Community (SADC)[5] is partially addressing this situation in the region, but the compilers are aware of gaps in the current listings (notably from Portuguese archives from Mozambique and Angola – these were widely available in Zambian Ministry libraries in the 1960s and 1970s).

Most known deep aquifer occurrences are found where the passive continental plate margins are encroached on by back arc basins deposits, as a continental plate and an oceanic plate slowly drift towards each other. This is best seen along the northern margin of the African Plate as it closes with the Eurasian Plate. Here the deposition sequence starts with mid Palaeozoic (Ordovician) tillites that are overlain by continental arkoses and red-beds and finishes within the mid-Cretaceous Nubian Sandstone before a marine transgression deposited a sequence of marine shales, dolomites, evaporites and limestones in the Palaeocene and Eocene in the Sirte Basin. Where this sequence has been deposited close to known basement highs, fresh groundwater has been encountered in

[4] The concept 'deep-seated aquifers' as used here does not include deep parts of thick aquifers that extend upwards to shallower depth, less than some 500 m below ground level.
[5] See SADC Groundwater Grey Literature Archive webpage (http://www.bgs.ac.uk/sadc/index.cfm).

the lower Palaeozoic sediments that merge into the Nubian Sandstone sequence (e.g. Mobil oil exploration wells concession 126-A1 and A3 drilled in 1968).

The groundwater occurrences in eastern Yemen, northwest Oman and southern Saudi Arabia are found in a similar sequence of sandstones and limestones with the prolific Cretaceous Mukalla Sandstone aquifer supporting irrigation developments in Wadi Hadhramaut, Yemen. At depths of 200-800 m below ground, the Lower and Upper Umm er Radhuma Limestone aquifers together with the Damman Limestone (Cramwinckel, 2010) are partially proven targets for deep aquifer development in the area to the south of the Rub al Khali and Umm al Hait (Muqshin oasis).

In the semi-arid Ogaden region of Ethiopia, a similar series of shallow late Palaeozoic and Mesozoic shelf deposits with shallow marine limestones followed by a continental sandstone sequence. Here drilling in 1977 near Gombor, 120 km southeast of Jijiga encountered semi-confined groundwater in the Adigrat Limestone under approximately 180 m of Jessoma Sandstone. The indications were the groundwater was recharged by influent seepage from spate flows in the seasonal Greer River to the west. The records of this borehole were lost during regional conflicts later in 1977, and 2007 Google Imagery shows a small compound at the well site.
Given the subsequent difficulties with providing water to satisfy the refugee situation in the region during the 1980s and 1990s, development of this resource could have been possible had legislation required this information to be lodged and recorded in a publicly available database. This would have saved expensive water trucking operations.

2.2 Governance issues

There are few specific provisions or regulations for the governance of deep-seated aquifers as a source of fresh water. Hence, they may be implicitly included in area-specific water or groundwater resources management plans (as far as existing), but usually not explicitly addressed because of their depth and the lack of information. A complication may be formed in several countries by the fact that beyond a certain depth mining laws are applicable and supersede water law, which may have consequences as well for institutional mandates and jurisdiction.

In relation to governance, it is important to note that most deep-seated aquifers are virtually isolated from the present-day active hydrological cycle. This makes them an ideal source for emergency water supply in cases where natural disasters (e.g. tsunamis, floods, droughts, earthquakes, etc.) have resulted in acute drinking-water shortage and degradation of shallower aquifers and wells. It makes them also insensitive to climatic variations and climate change, thus they may constitute important buffers in that respect. Some deep-seated aquifers may be converted from non-renewable to renewable aquifers as a result of exploitation, as this may induce recharge through or from overlying aquitards.

Enhanced governance may have a very significant impact on groundwater data collection, storage and dissemination, including data on deep-seated aquifers. Promising initiatives have been taken at several levels, although usually not specifically for deep aquifers. As just mentioned, at the regional level, the current SADC Groundwater Grey Literature Archive is partially addressing this situation for Southern Africa.

An additional aspect of hidden data concerns the results of the detailed geophysical reflection seismic surveys and drilling records that are collected and compiled by the international oil prospecting and production companies. Although the results of the deeper surveys (1 000 m+) have a high commercial value, the leasing national governments should insist that interpreted shallow information (depths of 500 m to 1 000 m) showing major faults, formation tops and bottoms and borehole geophysical logs should be made available to their natural resources and environmental agencies and that this should be included in the terms of the licensing agreement. This topic is covered under the heading “hidden data sources” in a recent International workshop on new technologies for the acquisition of information on transboundary aquifers organized by the International Groundwater Resources Assessment Centre (IGRAC) and the United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme (UNESCO-IHP, 2010), under the Global Environmental Facility - Transboundary Waters Assessment Programme (GEF-TWAP). While oil exploration reflection geophysical survey results are rarely made available, Figure 1 illustrates the type of detail that was available to supplement a hydrogeological study of the deep coastal aquifers in Lagos, Nigeria. This city with severe water supply problems relies on deep boreholes (800 m+), tapping the Cretaceous Abeokuta Formation limestone aquifer and the sand horizons in the Ilaro Formation (Nwankwoala, 2011).

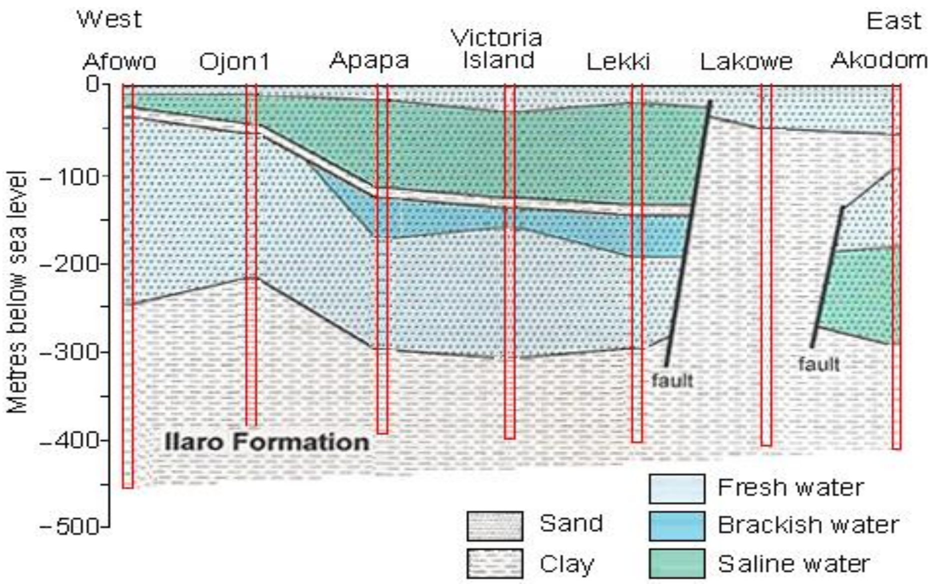

Figure 1: Section along the Lagos coast, Nigeria compiled from reflection seismic survey data and Lagos State Water Corporation borehole records. The section is approximately 20 km long (redrawn from Adelana et al.*, 2008)*

3. The Impact of Mining

Historically, the main ventures into the deep underground space have been for the mining of metallic and non-metallic minerals. This led to a steady development of pumps and power sources for mine drainage. Deep mining continues largely unrestrained by little effective governance in many countries. Even where belated governance has been introduced there are legacy issues. This is seen with the Cornish Wheal Jane Mine in southwest England where tin was extracted from the mid-18th century until 1992. Following abandonment, the mine flooded and acid drainage water escaped into the surface drainage. The subsequent remedial works were demanded under environmental legislation at a cost of over 300 million USD. Additional examples worldwide are highlighted by the fact that four out of the ten most contaminated sites are due to lead mining.

While engineering and geotechnical mining problems demand a closely focused approach on detail, groundwater appraisals require a much wider view of the geological setting of the problem.

3.1 An example - groundwater and mining in the Zambian Copperbelt

Mining in the Central African Copperbelt started around 1903. The Konkola (Figure 2) and Kabwe Mines (Box 3) in Zambia are located on the African Erosion Surface close to major water divides. The current 300 000 to 350 000 m^3/d of groundwater pumped from more than 1,500 m below ground level to dewater the workings at Konkola considerably augments the flow in the Kafue River (Engineering and Mining Journal, 2011). The dewatering pumping peaked at 425 500 m^3/d in 1978 (Mulenga and Chileshe, 1994). The copper ore bodies occur on the nose of the Kirilabombwe anticline of the late pre-Cambrian where early Palaeozoic Katanga Series tillites, conglomerates, sandstones and dolomites are folded against an ancient Basement Complex craton (Mulenga *et al.*, 1992). Arguably the wettest underground mine in the world (some 59 tonnes of groundwater per tonne of ore are lifted to the surface compared to a local norm of 4 tonnes per tonne of ore), it has been subject to numerous hydrological, hydrogeological and environmental studies.

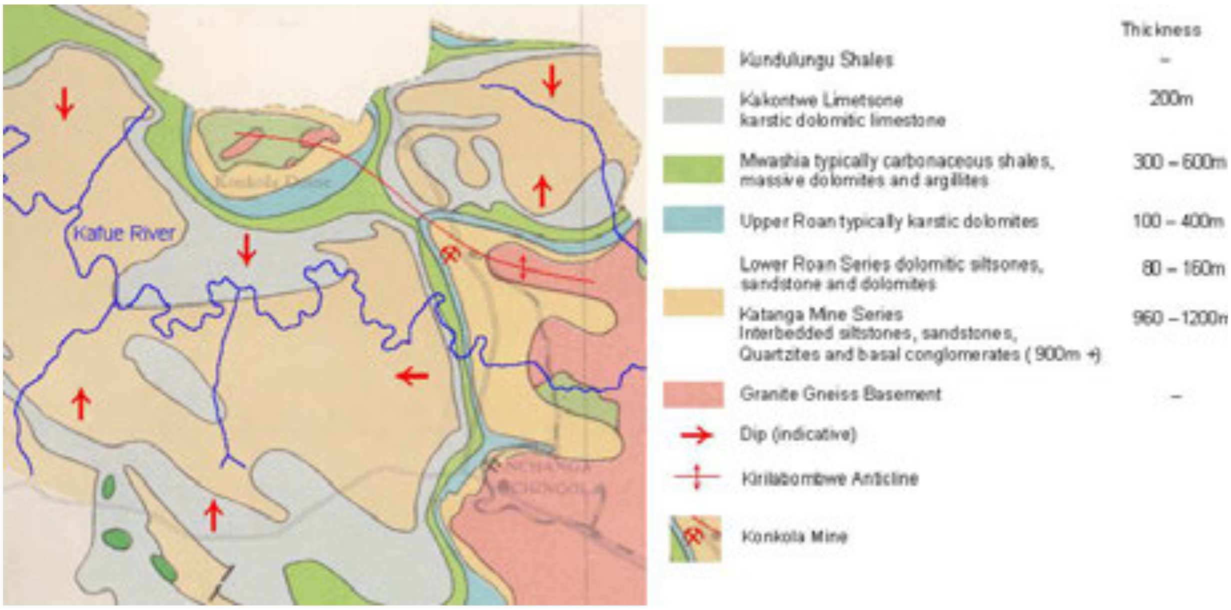

Figure 2: The geological setting of Konkola Mine, Zambia (based on the Geological Survey Map of the Copperbelt, 1961)

Since mining started, over 6 km^3 of potable groundwater (Simumba, 1993) has been pumped from the mine into the Kafue River. The source of this underground water was first suggested to come from the Kafue River. In the mid 1960s tests showed this was not the case and a regional groundwater source was tentatively identified. Subsequently in 1971, the Zambian Department of Water Affairs hydrogeologist, who was undertaking a detailed study of the hydrogeology of the Kabwe Lead and Zinc Mine (Jones and Töpfer 1972), examined the tectonic setting of the Konkola Mine and concluded that the active flow and recharge over local dolomite outcrops and the 400 km^2 synclinal structure extending to the southwest of the mine were the most probable sources. However, this has been questioned by Mulenga *et al.* (1992), who presented detailed chemical and isotope analysis and proposed a variety of surface water sources, including local streams, tailings dams and surface water ponds as contributors to some 45 percent of the dewatering flow. Based on this assumption, recommendations were made to line water courses or divert the local streams.

The main water-bearing horizon in the Konkola Mine is the 100-to-400-m-thick strongly karstic Upper Roan Dolomite, with the equally karstic Lower Roan Dolomite as a secondary source (Figure 2). Given the high permeability of the strongly karstic dolomites aquifers, the cone of influence is likely to be much more extensive than currently mapped. Less clear is the degree of hydraulic continuity between the mine and the younger karstic Kakontwe dolomitic limestone above the Mwashia Shale. However, given the extensive regional and local faulting and the lithological variations of the Mwashia Shale, under the heads introduced by the mine dewatering a high degree of hydraulic continuity is very likely to exist. The decline in the dewatering requirement since the 1978 peak of 425 500 m^3/day suggests that the extra 100 000 m^3/day came from the original confined storage in the Kakontwe and Upper Roan aquifers in synclinal basins to the north and south west of the mine. The extension of karstic flow zones under the Kundulungu Shales is plausible, given the extremely long karstic flow paths (500 km+) observed in Damman and Umm er Radhume Limestones of the Arabian Peninsula that supported the fresh groundwater springs offshore of Bahrain.

A wide ranging appraisal of the Zambian Copperbelt Mining Municipalities' water supplies foresees continuation of the 330 000 m^3/day as essential for maintaining the flow in the Kafue River and will have to be sustained at a high cost if mining at Konkola ceases (Norconsult, 2004 and 2005): the Kafue River being the main source of most urban and industrial raw water supplies downstream of the Konkola Mine dewatering discharge.

When compared with the dynamic groundwater regime at the Broken Hill Lead Mine at Kabwe and given the comparative size of the synclinal basins, it is considered that contemporary recharge within the Konkola Mine dewatering cone of influence has the potential to support all the observed abstraction.

The pattern of increasing recharge to significant karst dolomite aquifers has been established moving north in Zambia from Lusaka to Kabwe to Ndola where the mean annual rainfall varies from 820 mm to 930 mm and 1 182 mm and mean recharge has been estimated at 12, 16 and 20 percent (Hadwen, 1972; Jones, 1971; Jones and Töpfer, 1972). However, these estimates have since been found to be low, and a value of 20-25 percent (170 to 215 mm) of the revised mean 1963-1993 rainfall of 857 mm is now accepted for Lusaka (Nick, Museteka and Kringel, 2010). This would suggest that the earlier estimates for Kabwe and Ndola are less than half of correct recharge value (see Table B3-1)[6].

Translating the calculated infiltration based on the analysis of daily data as recharge to the Kakontwe dolomitic limestone at Kabwe shows how the recharge is less dependent on the total wet season rainfall and more dependent on the pattern of the rainfall (Jones and Töpfer, 1972). This pattern has also been observed by a Blind Geographic Routing (BGR) team reporting on the Development of a Groundwater Information and Management Program for the Lusaka Groundwater Systems (Bäumle and Kang'omba, 2009). Reporting on the same project, Nick (2011) presents maps showing large areas with mean annual recharge to the Lusaka dolomite aquifer exceeding 40 percent of the annual rainfall. Additionally, the Lusaka Dolomite outcrop dominates the southern lower-lying areas of Lusaka and has been historically legacy of major floods despite the aquifer being extensively pumped for urban, industrial and irrigation purposes: the most recent floods occurred in 2010.

Based on this sound information from similar dolomitic limestone aquifers in Zambia, it is entirely reasonable to expect that the underground workings will rapidly fill to the original groundwater levels and that the regional hydrological regime will readjust to close to the pre-mining development conditions within a few years of shutting down the dewatering system pumps.

[6] Burdon and Papakis (1963) plotted similar relationships between precipitation and infiltration for a number of Mediterranean karst outcrops.

Box 3: Groundwater at Broken Hill Mine, Kabwe, Zambia

When opencast mining commenced in 1906 the water levels stood between 1.2 m and 6 m below ground, depending on the season. Underground mining started in 1938 when the Davis Shaft was completed to 330 m and ceased in 1995. The ore body occupied the core of a synclinal basin groundwater catchment to the mine was estimated to cover around 45 km^2.

Between 1950 and 1952 the Davis Shaft was deepened to 486 m. In response to exceptionally heavy rains in the 1951-52 season (1 283 mm) that caused flooding of the underground workings, the pumping capacity was increased to 118 200 m^3/day. During the underground mining, the water level in the Davis Shaft was held at 456 m during the rainy season and at 420 m during the dry season. Figure B3-1 A) shows the abstraction from the mine from 1961 to 1971. The average volume of water pumped from the mine per year is 50 000 m^3/day.

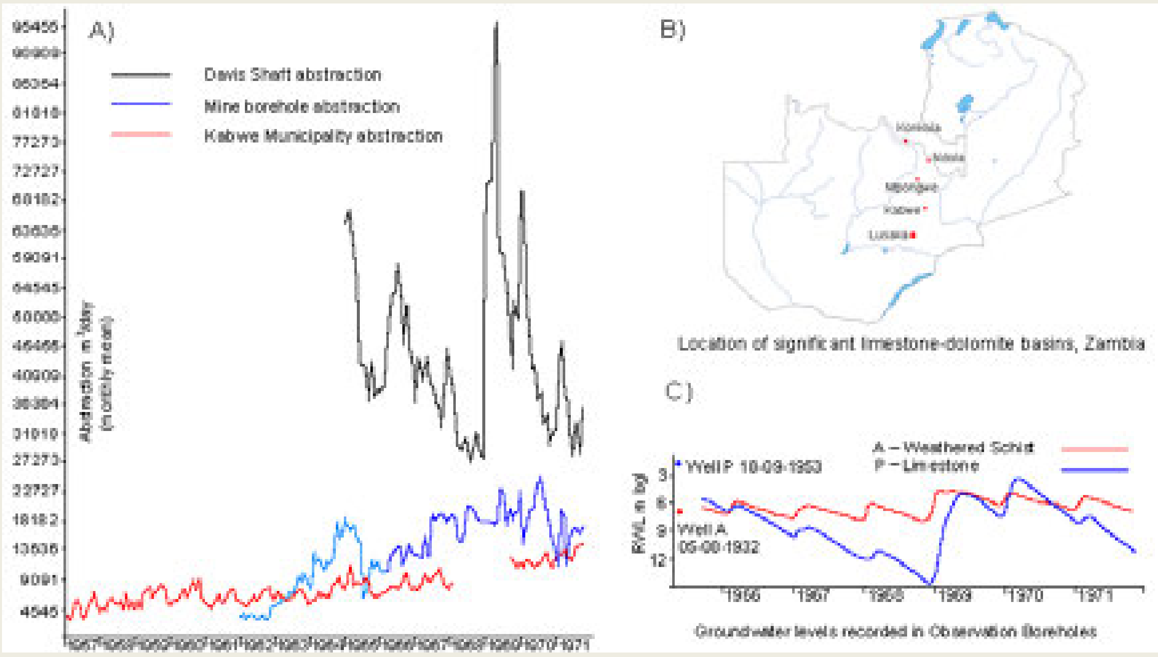

Figure B3-1: A) Broken Hill Mine – mean monthly Davis Shaft abstraction; B) location of some sinificant karstic limetsone and dolomite aquifers on the African Erosion Surface and on or close to the Kafue-Luangwa water divide and C) Groundwater hydrographs for observation wells outside mine cone of influence.

The calculated infiltration values shown on Table B3-1 can be equated to recharge and correlate with the dewatering abstraction from the Davis Shaft at the mine (Figure B3-1 A). The well hydrographs are from sites remote from the mine and close to the local groundwater divides.

Table B3-1: Water balance calculations for the Kalulu Dolomitic Limestone Aquifer – Kabwe, Zambia

Year	Precipitation	Rainfall Surplus*		Infiltration	
	mm	Mm	%	mm	%
1966-67	807	300	37	127	16
1967-68	737	91	12	145	20
1968-69	1 450	1 126	71	970	66
1969-70	841	393	46	457	54
1970-71	833	317	38	218	27

* Calculated from daily rainfall, potential evapotranspiration and soil moisture deficiency

Figure 3: Munkumpu and Mpongwe groundwater based irrigation projects, Zambia (Google Earth Image).

Among the recommendations made in 1971 by Department of Water Affairs hydrogeologists was for the development of large-scale groundwater-based irrigation schemes that would tap the Kakontwe and Upper Roan karstic aquifers around to the west and south of the mine. The proposed target abstraction was set at 2 to 3 m^3/s. Intriguingly at the time this suggestion was made, the mine operators at this time (Nchanga Mines) were planning the Munkumpu irrigation development based on a 1.5 m^3/s karstic spring discharging from a synclinal structure to the west of Mpongwe where the Government of Zambia were to develop a pumped groundwater irrigation development: currently some 3 500 ha are under irrigation at these developments that were merged in 1998 (Figure 3).

While engineering and geotechnical mining problems demand a closely focused approach on detail, groundwater appraisals require a much wider view of the geological setting of the problem. In the case of Konkola Mine, its location on the African Erosion Surface implies sound knowledge of the geomorphological development and hydrological response of this land surface. Thick soils and low gradients point to low-surface water runoff and high evaporation losses across the areas of deeply weathered crystalline basement. Here the low recharge rates assigned in many past regional studies are appropriate, whereas they are certainly not appropriate for the limestone and dolomite blocks where high recharge and perennial springs commonly are the main source for surface water streams. A further observation can be made regarding the prevalence of the high infiltration capacity of the soils (+50 mm/hr) supporting the ubiquitous Miombo forested interfluves of the main water course on the African Surface (Webster, 1965; White, 1983). These interfluves generate very little surface water runoff but retain the infiltrating rainfall in the soil profile and local perched aquifer horizons.

3.2 Governance issues

Preparing guidelines to ensure that future frontier resource assessments are adequately staffed by professionals with the right expertise and who have, or are given access to the appropriate information presents a governance problem in a climate where financial institutions and clients priorities are based on minimum costs. This elusive need is nowhere more clearly seen than when costly and long-term developments are being considered. The mining industry visibly needs to be regulated by institutions that do not only look at mining profits, but also take possible externalities into account.

4. The Impact of Oil and Gas Development

Oil and gas wells are the second widest scale intrusion into deep underground space after water wells. For example, just in the USA, in 2009 there were 363 107 producing oil wells and 460 261 producing gas wells[7]. There are over 1.5 million injection wells used for oil and gas recovery and for disposal of oil field production brines (by volume, the mean ratio being 7.5 brine to 1 of oil produced)[8].

An overview of the geological setting of the major onshore and certain offshore hydrocarbon provinces shows that many coincide with or are located near significant groundwater occurrences. With the exception of the African rift basins, the tectonic setting of most major hydrocarbon provinces match those identified as suitable for carbon dioxide (CO_2) storage (Figure 4).

Figure 4: Sedimentary basins showing suitability as sequestration sites (from IPCC, 2005).

All phases of hydrocarbon exploration, production and abandonment can pose a risk to groundwater resources and are subject to strict environmental controls, but unfortunately accidents occur: the majority of these are the result of human error and are avoidable. This would appear to place them beyond the role of governance and into the realm of the insurance sector where problems can be subject to risk assessments.

While the industry has ample experience in drilling exploration and production wells, there are always a range of problems associated with the loss of control over high pressure zones that can lead to a severe pressure kick or full-scale well blowout. Depending on the drilling phase, shutting in a high-pressure kick can force the reservoir fluids and gases into overlying permeable geological horizons. In the case of the Iranian Masjid-i-Sulaiman Oilfield, during the 1960s a deep exploration well targeting a Jurassic prospect leaked high pressure gas into the overlying, producing Eocene oil bearing horizons[9]. This disturbed the hydraulic balance in the upper producing zones and the formation brine displaced the oil in the Eocene production zones that had been in production since 1908. Although in this case no groundwater resources were reported to have been affected, it highlights the potential for the rapid transmission of reservoir brines and hydrocarbons into overlying aquifer horizons.

The consequences of any deficits with the well construction related to the integrity of the casing and/or grouting can lead to problems during the operation of production-phase oil and gas wells. Holes in the casing or leakages between the casing and the well wall can allow formation fluids to migrate into overlying aquifer formations.

A substantial area of the Midwestern hydrocarbon province in the USA is overlain by the High Plains - Ogallala - Equus Beds (Kansas) Aquifer (Figure 5). The hydrocarbon-bearing rocks were deposited during the Palaeozoic

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[7] See United States Energy Information Agency website (http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html).
[8] See United States Energy Information Agency website (http://www.gwpc.org/e-library/documents/general/Injection%20Wells-%20An%20Introduction%20to%20Their%20Use,%20Operation%20and%20Regulation.pdf).
[9] Source: 7th World Petroleum Congress, April 2 - 9, 1967 - World Petroleum Congress, Document ID 12276.

and Mesozoic along with substantial halite (NaCl), gypsiferous ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$) evaporite horizons that are recognized as potential sources of contamination to the overlying High Plains Aquifer.

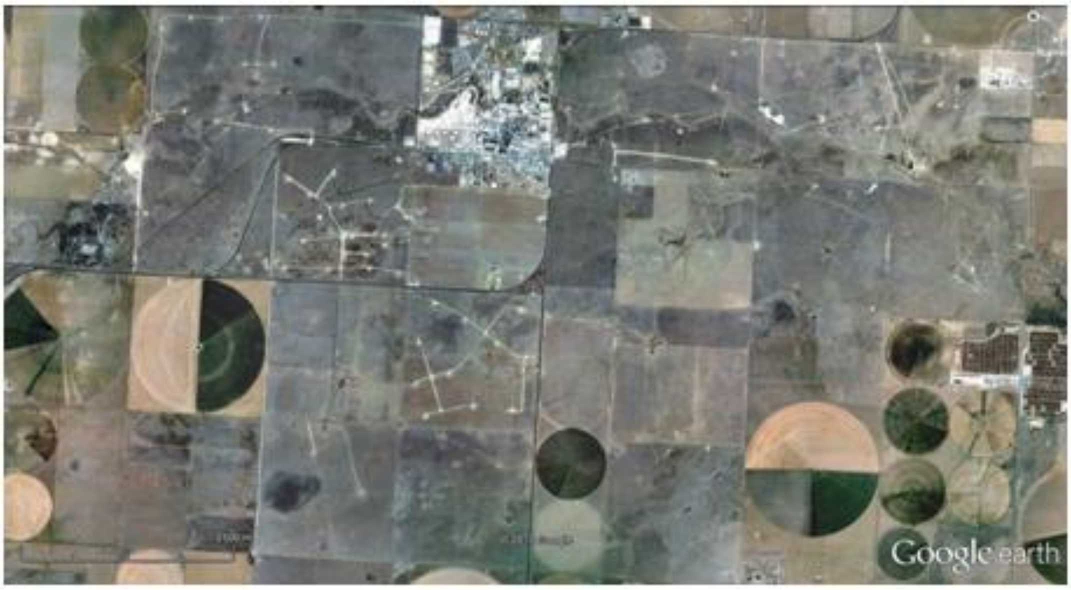


Figure 5: The juxtaposition of groundwater and oil wells on the Ogallala Aquifer in Moore County, NW Texas. (Valero McKee Refinery top centre of image: Centre pivot irrigation and spider traces link oil well sites). Google Earth Image.

Detailed studies in Kansas (Whittemore, 1997, 2004 and 2007) identified a range of aquifer contamination sources and problems that have been brought under control by a continuously evolving, but largely retroactive, governance regime. The solution of halite during early oil well drilling problems caused many localized cases of subsidence (Walters, 1978) but the main source of the groundwater salinization identified in the overlying aquifers are oilfield brines. These are chemically differentiated by a bromide signature. Originally, the oilfield brines were disposed of in surface ponds and local drainage systems but, since this practice was banned, on-going groundwater contamination is traced to the use of enhanced recovery wells where brine injected below the hydrocarbon trap leaks into the fresh water aquifer occurrences.

4.1 Specific governance aspects associated with hydrocarbon developments

In general, the USA and Western European environmental agencies have set out strict regulations and guidelines to protect groundwater resources but also accept that accidents are bound to happen and, therefore, have to rely on the development of clean-up measures and on the imposition of punitive fines to attempt to control the industry.

In a widespread review of the impacts of oil and gas exploration and production in Kansas, Walters (1978) describes how in the early 1930s, attention began to be given to the plugging of abandoned and closed oil and gas wells as these were increasingly being identified as sources of aquifer salinization. At first regulations were weakly enforced and the techniques employed were insufficient to prevent aquifer contamination. However, when further regulations governing the plugging of abandoned wells were introduced in 1935, they had to be revised as a series of ever-more stringent abandonment regulations by State environmental agencies to protect the aquifers, and these regulations had to be extended to cover all forms of drilled wells including abandoned water wells, mineral exploration and geotechnical investigation boreholes.

While the oil and gas companies have strong commercial interests in ensuring the industry standard engineering technology is applied to the construction of investigation and production wells, they can also have equally strong commercial reasons for avoiding the additional costs that may be required by external environmental regulators. By the second half of the 20th century, major oil companies had built up a very questionable legacy of bad practices in many oil and gas provinces. In addition, these companies are adept at evading any subsequent penalties arising from cavalier practices as seen in the Niger Delta, where the environmental damage places it in the world 'top ten' of worst contamination events.

In contrast to the mining sector, where engineering and financial management dominates, geologists occupy the higher management positions in most oil and gas exploration and exploitation companies. This ensures that the latest and often very expensive techniques and surveys are applied to the resource investigations and developments. The results of this approach have provided much of the material used in to establish the geological principles set out in this paper. However, when it comes to the engineering aspects of drilling oil and gas exploration and production wells and of processing installations, the industry becomes engineering- and cost-conscious, and corners are cut despite the best efforts of the industry regulators: the 2010 Deepwater Horizon blowout in the Gulf of Mexico is just one of an on-going series of similar industry failures where the onshore events can impact on the local groundwater resources.

Countries with weaker legislation or enforcement capabilities are likely to be faced with a growing legacy of resource and environmental problems. It is felt that such countries should review their oil and gas licensing agreements and include ample internationally-recognised indemnities to cover all potential resource and environmental degradation. As this will incur additional costs to the operators, and ultimately to the consumers, which the oil and gas companies will try to avoid, it is considered that either the World Trade Organisation or the other relevant United Nation's agency should design and implement such insurance cover by using an escrow account on behalf of the oil and gas exporting nations.

Table 2: Design attributes and principles of unitization versus common-pool resources (adapted from Jarvis, 2011)

Principle or attribute	**Unitization**
Conceptual development	1890–1930s
Boundaries	• Voluntary units • Compulsory/conservation units • Geographic units • Geologic units
Rules	• Pre-unit agreements at appraisal • Unitization agreement at pre-development • Redetermination during development
Collective action	• Collectively beneficial • Allows sharing of development Infrastructure • Avoids unnecessary wells and infrastructure occurring under the competitive rule of capture
Monitoring	• Uses pressure maintenance on the reservoir • Uses best technical or engineering Information • Provides foundation to carry out a secondary recovery programme
Sanctions	• Gives all owners of rights in the common reservoir a fair share of the production
Dispute resolution	• Pre-unit agreement • Industry-standard agreements • Redetermination process
Rights of regimes	• Can be developed through voluntary or government-mandated compulsory action
Administration	• Voluntary to compulsory • Other alternatives (e.g. sole development, partitioned development, fixed equity, buy-out or asset swaps)

Besides national and local government environmental regulation of the oil and gas industry, in the first half of the 20th century many oil production companies in the USA developed a significant pooled or unitized approach to their resource development. This industrial solution aimed at resolving problems that arose from uncontrolled production rates and from the common feature of early oil production in the USA known as "offsetting", where a landowner drilled a successful oil well near his property boundary and his neighbour, observing the success, responded by drilling an oil well on his property as close as possible to the successful well. The uncontrolled production frequently disrupted the hydraulic balance within the oil reservoir and resulted in up-coning of saline-formation water from below that broke up the continuity of the oil layer. The oil-well operators rapidly became aware of the damage caused to the reservoir and the resulting reduction in their collective oil recovery.

In response to this problem, the oil operators adopted a control model based on the concept of resource unitization where each operator received a prior agreed quota of the overall field production (Knowlton, 1939). The resource unitization model is based on the concept that the most successful and, therefore, profitable development of an oilfield is achieved by establishing and maintaining a controlled extraction regime that sustains a steady and laminar flow of the oil and formation fluids to the oil wells. The mutual benefits in maintaining this extraction regime to all producers from the oilfield demonstrated to be in the best long-term common interest. Even if some producers had to settle for a lower overall yield, their benefits were still possibly greater than if the producers had been engaged in a race to the pumps. The basic features of the resource unitization model are shown in Table 2.

5. Geothermal Energy

Groundwater, likewise surface water, may be considered as an energy source. In fact, the layers of rock that make up the Earth's surface grow increasingly hot with depth, from crust to mantle to core, and this heat – held in rocks and groundwater – can be tapped as energy. The heat content of groundwater increases constantly with depth, even in average gradient conditions (30ºC/1 km). When thermal anomalies, linked to volumes of magma intruded near to the surface or to deep reaching fractures, are present at shallow crustal levels, groundwater may reach temperatures up to over 400ºC at economically viable depths (see Box 4). The heat content of groundwater, either transformed into electricity (high temperature systems) or used directly (e.g. heating), is known as geothermal energy.

Geothermal energy remains today an underdeveloped energy resource compared to the vast amount of thermal energy contained within the Earth's crust. The total heat flux through the Earth's crust has been estimated to be 42 x 106 MW and the total heat energy above 15°C stored within it is on the order of 5.4 x 1021 MJ. Mankind's present total annual primary energy consumption is estimated at 4.2 x 1011 MJ per year (OECD/IEA, 2004), which is negligible compared to the heat stored in the crust: the geothermal energy resource base is thus enormous. There are however serious technical and financial limitations to how large a proportion of the energy can be harnessed as an energy supply for humanity: (i) production wells must be drilled, and technology currently available does not allow to drill deeper than 5-10 km; (ii) there needs to be a circulating fluid to extract the heat from the hot rock and bring it to the surface; (iii) the amount of useful heat that can be extracted is very limited; (iv) there are theoretical limitations to the conversion of heat to electricity or other energy carriers; and (v) energy production from geothermal energy has to be accomplished at competitive prices. The main challenge for geothermal development is to overcome these barriers and give the world access to a huge resource that will last thousands of years.

Box 4: Economic considerations in geothermal energy

Capital costs for conventional geothermal electricity are in the 1 000-3 800 €/kW range, resulting in 40-80 €/MWh. Enhanced Geothermal Systems (EGS) investment costs are much higher given the experimental nature of the technology (10 000-26 000 €/kW) and result in a cost of 170-350 €/MWh. Capital cost for heat supply from conventional sites is in the range of 100-300 €/kWth, resulting in a cost of 4-7 €/MWhth. Heat supply costs from EGS are only speculative at one tenth the EGS electricity costs. The single item that has the highest impact on costs is drilling, typically 30-50 percent of total development cost for electricity generation. Well costs can vary from a few tens of thousands to several million euro for high-temperature wells for electricity generation. Piping costs vary from 200 to 6 000 €/m in highly developed urban areas. Drilling two boreholes, known as a doublet, to a depth of 3 000 meters can cost up to 14 million EUR. Insurance premiums can cost up to 25 percent of the sum insured. Over half of the total production costs over the lifetime of the project are expenses associated with the well field. Up to 50 percent or more of the wells might have to be replaced over the course of the project, possibly increasing levelled electricity cost by 15-20 percent.

The installed cost of heat pumps vary between 1 000 and 2 500 €/kW for typical domestic facilities of 6-11 kW, and between 1 700 and 1 950 €/kW for industrial or commercial installations in the 55−300 kW range. Capital costs depend greatly on the ground exchanger layout, whether horizontal or boreholes. Data from Greece suggests capital costs between 1 200 and 1 500 €/kWth, electricity and maintenance costs of 28 €/MWhth, giving total costs of 48 €/MWhth (including capital amortization over 20 years with 5 percent cost of borrowing money). This has to be compared with diesel oil: 72 €/MWhth; natural gas between 58 and 65 €/MWhth and air source heat pumps of 60 €/MWhth. Of the estimated 81 billion EUR (120 billion USD) invested in renewables worldwide in 2008, around 6 percent (4,9 €/m) were directed to geothermal heat and power.

The system availability for a geothermal energy plant can reach 95 percent. A modern electricity plant can reach a 92 percent load factor (8 000 full-load hours), whereas actual national figures vary from 60 to 85 percent. The mode of operation determines these load factors: whereas most plants are operated as base-load supply, thus reaching high load factors, the depletion of the reservoir may force peak-load operation, reducing the load factor accordingly. Heat pumps have a lower actual factor at around 20 percent, whereas other heat uses reach load factors of 20 to 60 percent.

Various levels of technological maturity exist, depending on the specific energy product (electricity or heat) and, in the case of heat, the conversion process, where geothermal energy may be used directly (e.g. district heating) or indirectly (e.g. heat pumps). The technologies used to transform the heat into electricity are mostly linked to the temperature and pressure of the geothermal fluid. Direct steam turbines use natural high-temperature steam resources directly to generate electricity, and result in the lowest power plant cost. For the high temperature mix of brine and steam, a flash steam plant separates the steam from the liquid and then expands it in a turbine. If the resource has lower temperatures (e.g. between 120 and 180°C), a binary cycle plant is more efficient and has better environmental performance, although it is more expensive. Beyond pure electricity generation, geothermal combined heat and power (CHP) is a natural energy-efficiency option used, for example, in district heating networks.

Electricity is generated from geothermal energy in 24 countries. In 2002, geothermal energy occupied the third place worldwide amongst renewable sources to generate electricity, after hydropower and biomass. In 2002, electricity production from geothermal energy in the world totalled 57 TWh, compared to 52 TWh from wind power, 1 TWh from solar power (photovoltaic) and 2610 TWh from hydro-power (OECD/IEA, 2004). The relative growth in wind and solar energy has in recent years outstripped that of geothermal energy, reflecting strong investment for research and development in these sectors compared to geothermal energy. Geothermal power plants are, contrary to wind and solar energy plants, well suited to producing an electrical base load. Total installed geothermal power today is about 10 GW, 92 percent of it generated in conventional power plants, while 8 percent is generated in binary plants. The Global Geothermal Power and Heat Pump Market Outlook 2010-2015 estimates an average annual growth of 14 percent of geothermal electric generation and direct uses together, from 661 200 MW of 2010 to 120 300 MW in 2015. For electricity generation only, the report indicates an annual growth of the installed capacity of 12.4 percent, from 10 500 MW in 2009 to 19 200 MW in 2015. Direct uses of geothermal heath[10] will grow 14.9 percent annually, from the present day 50 500 MW to 101 100 MW at the end of 2015.

5.1 The new geothermal frontiers

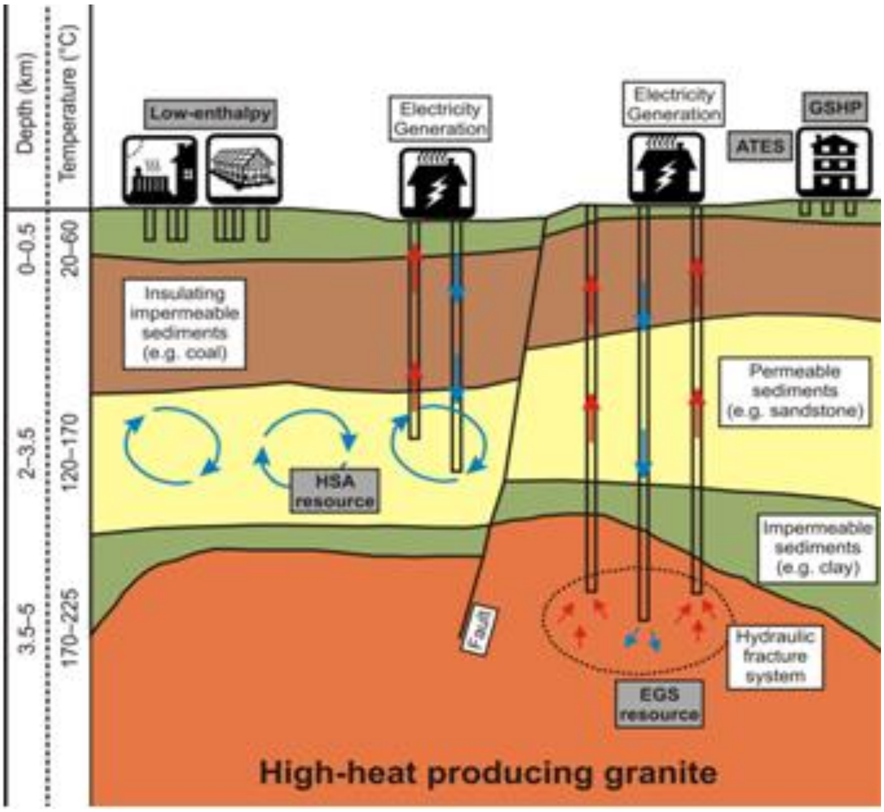
The Hot Wet Rock (HWR) and Hot Dry Rock (HDR) Systems

The water associated with the hot wet rock geothermal occurrences may be of deep-seated, juvenile origin or recharged by groundwater flow. Hot wet rock occurrences are the main source for current geothermal electricity generation. Geologically the wet rock occurrences are associated with obviously active igneous terrains. The hot dry rock geothermal systems are artificially created by drilling into hot impermeable rock: the necessary permeability is created by high pressure hydro-fracturing. Several attempts were made in early 1970s to produce energy from impermeable hot dry rocks, including experiments to create a sufficient network of permeable pathways within deep the target heat sources to allow for the circulation of the heat extraction fluids between the injection and extraction wells at Fenton Hill (target at 3 km) in New Mexico, USA, Rosemanowes (3 km) in the United Kingdom (UK), Ogachi (1.3 km) in Japan and in France and Germany where the targets are between 4.5 and 5 km below ground level (MIT, 2006). None of these was entirely successful due to hydraulic fracturing opening the pre-existing anisotropic planes of weakness (fractures and fissures) within the rock, rather than creating new random fissuring and permeability as is the case with oil well hydraulic fracturing. The result of this fracture pattern is the creation of preferential flow paths between the injection and abstraction wells that in effect short-circuited the heat abstraction capacity.

Enhanced Geothermal Systems (EGS)

In recent years, interest has been growing for developing the concept of EGS. Unlike HDR systems, EGS systems are not only high-temperature anomalies in the crust but also have some primary permeability, which needs to be enhanced to make production feasible. Several projects of this type are now ongoing in the world like in Soultz-sous-Forêts in France, Groß Schönebeck in Germany, and the Cooper Basin in Australia. This latter is presently attracting considerable interest, as many companies are now attempting to enhance an over 200°C geothermal reservoir in a huge 4-5 km deep sedimentary basin underlain by a heat source – a large mass of granites. If successful, geothermal energy could rapidly become Australia״s main source of electric power and facilitate similar geothermal projects elsewhere.

[10] Heath pumps account for 67 percent of direct geothermal uses, with accelerated growth in Germany, Holland, Norway, Sweden and the USA.



Key:
GSHP - Ground Source Heat Pumps
ATES - Aquifer Thermal Energy Storage

Figure 6: Schematic diagram showing low and high enthalpy geothermal energy systems (from Driscoll and Middlemis, 2011).

Supercritical Geothermal Systems (SGS)

Above 374°C and 221 bar pressure, water achieves supercritical condition. Fluid values are slightly higher if the fluid is saline. It has been calculated that the energy output per volume unit from a well with supercritical fluid can be as much as 5-10 times the energy output from a conventional high temperature system. Geothermal systems where such conditions prevail are called supercritical geothermal systems (SGS). It is already known that very high temperatures can be reached in high-temperature geothermal systems near or within cooling intrusions. For example, temperatures up to 340°C degrees have been observed in several high temperature systems in Iceland, Italy and China (Tibet), among others. Conservative extrapolation of temperature–depth curves indicate that temperatures above 400°C can be expected at 4-5 km depth, and the pressure there should be high enough to create supercritical conditions if hydrostatical pressure is assumed. In addition, extensional stress field and fracture formation revealed by frequent earthquakes indicate that considerable permeability should exist in recent fracture systems. Based on this information, a consortium of stakeholders called the Iceland Deep Drilling Project (IDDP) has been formed to drill three 4-5 km deep wells into Icelandic high-temperature systems to explore for SGS and to develop methods to utilize the fluid for electricity. The first well, IDDP #1 drilled in the Krafla geothermal system in northern Iceland, has produced superheated steam 12 hours after opening (T: 410°C, P: 40 bar, H: 3150 KJ/Kg) with a potential power output of 30-40 MWe. The well was closed on 11 August for modification on the flow line and pilot tests will begin about mid-September 2011. The main technical challenges include development of proper well design and suitable drilling methods, material selection to withstand highly corrosive fluids and methods to handle the fluid and convert the heat energy to electricity. The timeframe of this experiment will be on the order of ten years and will, if successful, have great replication potential in other high-temperature geothermal systems.

Ocean Floor and Submarine Geothermal Systems

The mid-oceanic ridges comprise a more than 50 000-km-long continuous chain on the ocean floor. These are places where hot mantle material is upwelling from the mantle and is emplaced as intrusions at shallow depths below ridge crests. The extensional tectonic environment causes tensional fractures, and strong hydrothermal circulation is observed forming hot springs on the ocean floor. Hot springs at great depths on the mid-oceanic ridges are known as "black smokers" where temperatures exceeding 370°C have been measured. These are places where water in supercritical state is injected into the cold ocean water exhibiting the huge energy reserves below the mid-oceanic ridges. As technology for exploitation of oil and gas in the deep oceans has developed rapidly in recent years, it is not impossible to envisage that production of geothermal energy at mid-ocean ridges will eventually be technically and economically possible.

Presently, an interesting and innovative project is being implemented in Italy: the Marsili Project, named from the Marsili submarine volcano (Eolian Island Arc), the largest active volcano in Europe. The project – now under way – includes the drilling of offshore exploratory wells into the volcano and the assessment of its geothermal potential, estimated to be large.

Hot Sedimentary Aquifers

The HSA systems (see Figure 6) are designed to extract and re-inject groundwater from hot deep-seated aquifer horizons (RPS Aquaterra and Hot Dry Rocks, 2012). These deep aquifers can be saline and precautions are taken to prevent contamination of shallower aquifer horizons. Lower empathy deep sedimentary aquifers with temperatures above 60°C can be developed using the Organic Rankine Cycle for heat extraction and this widens the areas where geothermal electricity generation is feasible: Figure 7 shows the potential for HSA resource potential on the UK mainland. Successful HSA developments rely on conduction and advection, and where induced temperature gradients and high vertical permeability exist, convection flow will improve the efficiency of the system.

Unlike HDR systems, HSA systems are not only high-temperature anomalies but also have inherent permeability that can be enhanced to make production feasible. Several HSA projects being implemented including those at Soultz-sous-Forêts in France, Groß Schönebeck in Germany, and the Cooper Basin in Australia where a number of commercial companies are attempting to enhance an over 200°C geothermal reservoir in a huge 4-5 km deep sedimentary basin underlain by a heat source (Figure 6). As mentioned earlier, if successful, geothermal energy could rapidly become Australia´s main source of electric power and facilitate similar geothermal projects elsewhere.

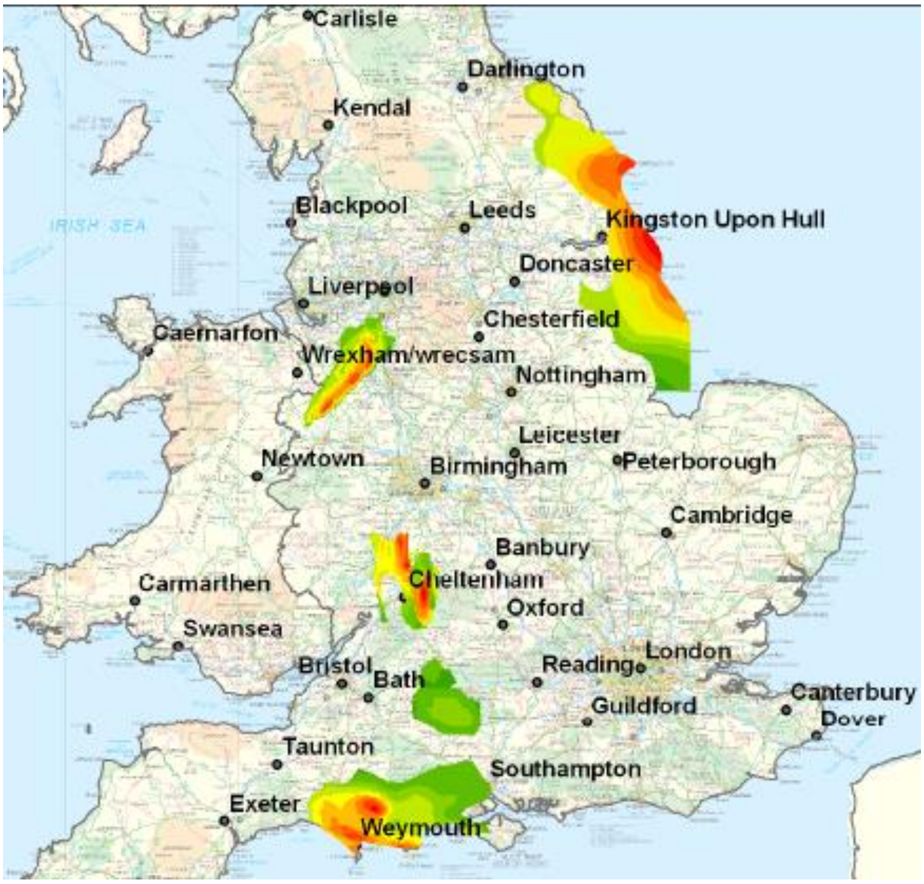


Figure 7: Main HSA basins on the UK mainland (from Busby, 2010). Temperatures at 2-5 km below ground level range from 50 to 105°C.

Geopressured Aquifers

A further advance in the potential HSA energy resources has been the identification in the northern sector of the Gulf of Mexico of deep over-pressured gas zones. These also occur in the Niger Delta (Section 3.5.2). Referred to as geopressured aquifers, they contain significant volumes of dissolved methane trapped in sedimentary formations at a depth of about 3 km to 6 km. The temperature of the water is in the range of 90°C to 200°C. Although theoretically a possible source for thermal energy, hydraulic energy and methane, they have not been systematically evaluated for economic development.

5.2 Specific governance issues for geothermal energy and impacts on groundwater

The potential impacts of geothermal energy generation on groundwater have been set out under the United Nations University - Geothermal Training Program as shown on Table 3.

Given the scale of geothermal existing and planned development even in the USA (Figure 8), future depletion of the available resource is unlikely to be of immediate concern, even though the localised rate of heat extraction from geothermal sources is estimated to be 10 times the natural geothermal replenishment[11].

The Massachusetts Institute of Technology (MIT, 2006) lists no less than twelve separate legislative controls to geothermal developments in the USA. The International Finance Corporation (IFC, 2007) refers to similar lists of international and national guidelines and legislation as providing the necessary governance controls for developments elsewhere in the world.

Table 3: Potential effects of geothermal developments on groundwater (adapted from Hunt, 2001)

	Low Enthalpy Systems – HSA	**High Enthalpy Systems EGS**	
		Vapour dominated	**Liquid dominated**
Drilling operations			
Contamination of groundwater by drilling fluids	1	2	2
Mass withdrawal			
Depletion of groundwater	0	1	2
Hydrothermal eruptions			
Ground temperature changes	0	1	2
Waste Liquid disposal			
Infiltration of surface disposal	1	1	2
Re-injection contamination of groundwater	1	1	1

Key	0 = no effect	1 = little effect	2 = moderate effect	3 = high effect

Given the very high costs of investigations and development adding to the known environmental risks associated with the hydrothermal fluids, the general governmental view would appear to be that all operators will apply the necessary precautions and risk management plans before undertaking tangible investigations and developments. Also on the side of governance, as with hydrocarbon developments, even with appropriate legislation, governments have to accept that accidents may happen and, therefore, rely on the application of clean-up measures and punitive fines to control the geothermal sector.

[11] See Encyclopedia of New Zealand website for more information (http://www.teara.govt.nz/en/geothermal-energy/5).

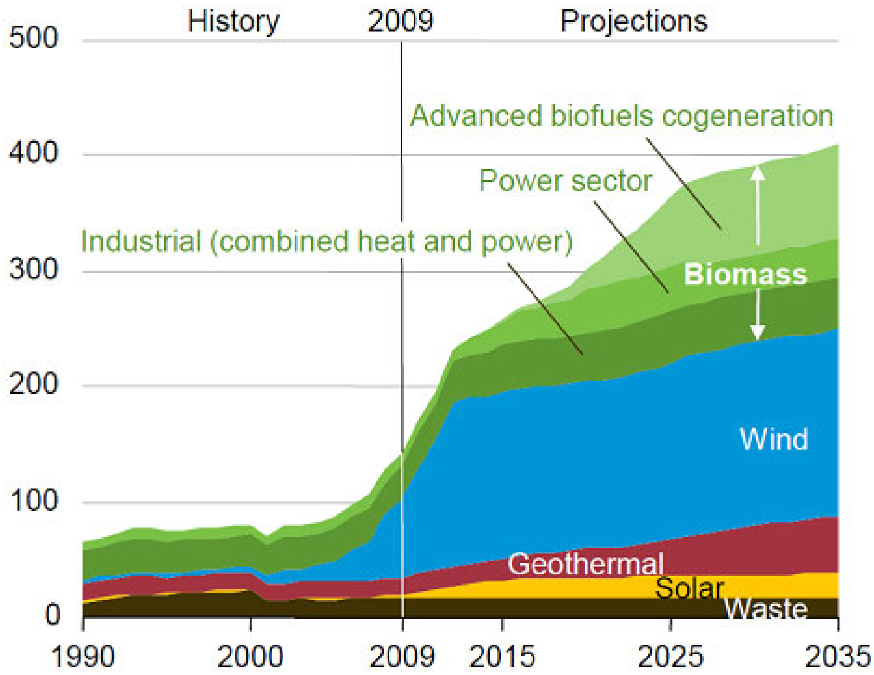


Figure 8: United States non-hydropower renewable electricity generation, 1990 – 2035 (billion kilowatts per year): From U.S. Energy Information Administration, 2011.

6. Disposal and Storage of Hazardous Wastes

Waste may end up in the subsurface unintentionally, for example by lack of adequate treatment and sewerage systems, through septic tanks or as a by-product of subsurface activities such as drilling (drilling mud, cuttings, etc.), mining or tunnelling. Not all waste of this category is hazardous but some of it certainly is, for instance PPCPs (pharmaceuticals and personal care products), EDCs (endocrine disruptive compounds) and radioactive residues (e.g. from hospitals). In an increasing number of countries, however, parts of the subsurface domain are used, or considered to be used, for planned storage of waste of different categories, including hazardous waste. Most notorious is the storage of radioactive waste from nuclear power plants. Other categories are the storage of carbon dioxide and the storage of various types of waste through deep-well disposal. Except for the storage of carbon dioxide (Carbon Capture and Sequestration, CCS), which will be addressed in the next chapter, these different categories will be briefly reviewed below. In addition, some information is provided on nuclear weapons testing and nuclear accidents, not intended as a form of disposal and storage of hazardous waste, but with some similarities.

6.1 Deep-well waste disposal

Deep-well injection is a technique for the disposal of liquid waste or solid waste that can be reworked to a slurry. In general, permeable formations with good storage capacity – such as sands, sandstones and fractured or karstic limestones – are required to receive the liquid waste, while effective impermeable cap rocks should be present to ensure that the injected waste remains permanently isolated from the biosphere. Injected hazardous waste should be trapped in deep formations for millions of years, like oil and gas. That is why injection sites should be free from seismic hazards. Injection depths are usually of the order of one thousand to a few thousands of metres.

The waste products to be injected originate from different sectors. They include: oil field brines, cuttings, drilling mud, sulphides, mercury compounds, arsenic, cadmium and other waste produced in the oil and gas industry; liquid waste from solution mining and other mining operations; all kinds of industrial and municipal liquid waste; and even low-level radioactive waste.

Deep-well injection follows technological protocols and governmental laws and regulations (not clear to what extent countries have these available and implement them carefully). For example, the USA distinguishes five injection well classes, to which State regulations refer. During recent years, oil and gas companies have become keener to comply with environmentally sound solutions for their E&P waste products, including deep-well disposal. Careful study of selected sites and detailed monitoring before, during and after injection are prerequisites for safe waste disposal. Although deep-well injection seems to attract the general public's attention less than radioactive waste and CSS activities, environmentalists occasionally oppose to newly proposed deep injection wells if they consider them to be risky.

6.2 Subsurface storage of radioactive waste

Radioactive waste ranks highest within the category of hazardous waste. Its potential subsurface disposal is still controversial and unresolved, although there is wide agreement that storing nuclear waste in a geologically stable and isolated location underground is a far more promising option than dumping it in sealed barrels into the ocean, which has been practiced for some time during the period 1940-1960. The problem of nuclear waste lies not only in the extremely devastating impact of potentially released radiation on the exposed biosphere (including humans), but also in the enormous persistence of its hazardous properties. Radiation half-lives of important nuclear waste components are in the order of thousands to millions of years, which means in practice that a safe repository should isolate the waste from the human environment for infinite time.

Sources of nuclear waste include the nuclear fuel cycle (front end and back end), nuclear weapons, medical and industrial waste, as well as fossil fuels. Often a distinction is made between low-level waste (containing small amounts of mostly short-lived radioactivity) and high-level waste (as produced by nuclear reactors). Uranium mill tailings, left over when ore is refined and processed, is the largest by volume of any form of radioactive waste, but their level of radioactivity is low. Spent rods in nuclear power plants contain radioactive fission products and actinides. These isotopes are formed in nuclear reactors and build up gradually to a level where they stop the chain reaction. The fuel in the reactor then has to be replaced by new fuel. The used fuel is either stored (e.g. in the USA) or reprocessed to remove the fission products and re-used (e.g. in Russia, UK, France, Japan and India). Spent fuel rods are high-level waste, and the mentioned reprocessing produces a very concentrated form of high-level waste as well. The annual production of high-level nuclear waste is approximately 12 000 metric tons worldwide.

Currently, various approaches to the disposal or containment of radioactive waste can be observed. Low-level waste is (or should be) disposed on controlled low-level waste sanitary landfills, sometimes after on-site containment for a number of years as to allow decay to a safe level. Cases of illegal dumping, however, are known (sometime in remote countries). Probably, most liquid low-level wastes are poured down the drain, whether or not they are still radioactive. Uranium mill tailings have been used as foundation and building materials, until their risk was discovered. Preferred ways of disposal nowadays are storage in clay pits, far from population centres, or in abandoned mines.

Current practices in managing high-level radioactive waste are a combination of temporary storage and investigating options for permanent storage. Nuclear waste is stored temporarily on-site at the power plant in specially constructed containment pools or transported to temporary containment facilities. Many countries have been studying already for decennia options for permanent subsurface storage. A suitable permanent repository should be geologically stable, isolated from the modern hydrological cycle and unlikely to be affected by seismic activity or to be disturbed otherwise for at least tens of thousands of years. Potential sites selected and studied in detail are in volcanic rock high above the water table (e.g. Yucca Mountain, USA), in crystalline rock (e.g. Finland, Sweden and India), in thick impermeable clay (e.g. Boom Clay Formation, Belgium) and in salt domes (e.g. Gorleben site, Germany).

6.3 Nuclear weapons testing and nuclear power accidents

Underground nuclear testing, which probably represents the most aggressive invasion, and the burial of radioactive waste are possibly the most heavily investigated aspects of the subsurface space. Atmospheric tests created a tritium peak that has been widely used for groundwater dating purposes. Around 2 010 underground nuclear tests have been carried out worldwide but, apart from the Nevada Death Valley Test Site (NTS) in western USA, only limited data related to groundwater has been made publicly available. Most terrestrial underground test sites are located in arid or semiarid climatic areas with very deep (>200 m) groundwater levels (Figure 9).

The French conducted undersea testing in the lagoon of Moruroa Atoll in French Polynesia and, despite the extreme military secrecy, the heat generated by the tests produced a geothermal convection cell that created a water percolation rate of 10 m/year. At this rate highly radioactive material is expected to reach the floor of the lagoon within 50 years instead of the 500 to 1 000 calculated before the tests. The hydraulic circulation of the geothermal cell is considered to have been assisted by the shock fracturing of the underlying basalt seamount. By the late 1980s, radioactive cesium-134 that could have only originated from the test was detected during surveys in the lagoon at Moruroa. When limited test data was compared with these surveys, it became clear that in some cases the cesium-134 migrated to the lagoon floor within six years. As a result of these findings, plans to use Moruroa as a long-term nuclear waste site should be ruled out and essentially the atoll is already a leaking nuclear waste dump.

Over 800 underground tests were conducted at the USA NTS (Fenelon, Sweetkind, and Laczniak, 2010) and considerably fewer in the Marshall Islands in the Pacific. A number of tests vented to the surface. Most formed debris chimneys and subsidence craters (Figure 10). Groundwater contamination as a result of the underground tests is acknowledged and has been thoroughly investigated under the direction of the US Department of Energy. The main mechanism for radioactive species to enter the groundwater flow systems include leaching of the more soluble elements[12] that condensed in the rubble chimney after the test: less radioactive material[13] is leached from the melted and fused rock and bomb debris that formed at the base of the explosion cavity.

[12] Dominantly the more volatile alkali metals, uranium, antimony and tellurium.
[13] Dominantly plutonium and the rare earth elements.

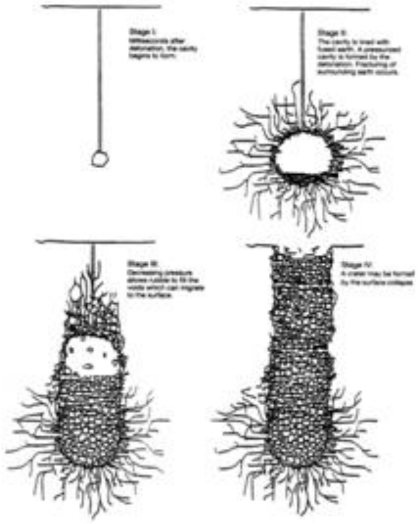


Figure 9 (above): 1945-1998 Sites of over 2,000 Nuclear Test Sites (from Atomic Archive[14]).

Figure 10 (right): Schematic diagram of the formation of a debris chimney associated with an underground test (US DOE, 1996).

Accidents form another mechanism of unintended nuclear pollution of the environment, including the subsurface. The impact of the 11 March 2011 Tōhoku earthquake and tsunami on the Fukushima Dai-ichi nuclear power station has brought the safety of nuclear power plants into public focus with Japan suspending and Germany phasing out all nuclear power generation.

Since the introduction of nuclear power plants in 1952 there have been 16 incidents rated at 3 or over on the International Atomic Energy Agency's 7-fold scale[15]. The worst incident was the 1986 Chernobyl explosion (rated at 7) that caused severe environmental contamination over a wide area.

6.4 Groundwater governance issues arising from disposal of hazardous waste

From the governance point of view a number comments can be made: hazards presented by some low-level waste may continue far beyond the formal landfill control period. Information on nuclear weapon production is top-secret, which is an obstacle to ensuring proper handling and storage of the corresponding nuclear waste.

Many countries have their laws, plans, regulations and standards on radioactive waste management. Standards on permissible doses of permitted exposure to radioactivity are in many European countries more stringent than proposed in the USA or suggested by the International Commission on Radiation Protection.

Nuclear energy and the related environmental and health risks are politically sensitive and receive ample attention from citizens. The latter (in particular organized groups of activists) may block options or solutions and thus constitute a factor in the decision-making process. In various cases, activists have tried to prevent the transport of nuclear waste. On the other hand, several countries organize public consultations to get stakeholders involved, so there is a variable picture.

Some countries depend on nuclear power (e.g. France, Switzerland, Japan, UK, Canada and Russia) but have made very limited progress in selecting and studying permanent repositories for high-level nuclear waste.

International governance is provided by the OECD Nuclear Energy Agency's Radioactive Waste Management Committee (RWMC) and the International Atomic Energy Agency (IAEA). However, the political and public on-off relationship to nuclear power generation has been largely driven by fear of reactor explosions and melt-downs plus health concerns over environmental contamination caused by inadvertent leaks and the ultimate safe storage of potent radioactive waste products. Although readily detectable at very low concentration, radioactive elements and compounds are also a major health hazard at equally low concentrations. This should place all forms of nuclear energy usage under strong international governance. The long half-life of the transuranic elements is seen as adding to the risks.

[14] http://www.atomicarchive.com/Almanac/Testing.shtml.

[15] See IAEA website for more information(http://www-pub.iaea.org/MTCD/publications/PDF/INES-2009_web.pdf).

These risks have led democratic governments to adopt a highly hedged approach to the problem. The early nuclear supporters claim – that nuclear power would ultimately be so cheap to produce that it could be virtually supplied for free – remains attractive. However, past experience has shown the human error and mechanical failures are hard to legislate against and equally hard to rule out.

7. Injection and Recovery Applications

7.1 Injection and recovery for mineral extraction

Developments in drilling and pump technology enable solution mining of salt to become rapidly established in the second half of the 19th century. Whyatt and Varley (2008) for example report of the collapse of a solution mine in 1873 at Varangeville Mine, France. Until the 1950s solution mining was largely limited to the use of water or steam to extract water-soluble chloride and bicarbonate salts of sodium, potassium and magnesium.

The use of acid based and other chemical extraction methods started in 10th century China with the leaching of copper using sulphuric or hydrochloric acid from copper carbonate, oxide and silicate mineral occurrences. The chemical leaching solutions are referred to as lixiviants, and all are hazardous to Underground Sources of Drinking Water (USDW) aquifers. Currently 16 copper mines in the USA are using *in situ* leaching of copper mining. Solution mining of uranium began in the USA and Russia in the 1960s using acid based lixiviants but, since the 1970s, solution mining in the USA uses a carbonate based lixiviant. Geologically, the uranium ores occur in porous sandstone aquifers. Other uses of solution mining are for the extraction of sulphur and gold.

The United States Environmental Protection Agency (US EPA, 1999a) undertook a study of injection wells used for solution mining. This report clarifies the situation differentiating various classes of injection wells (see Appendix 1). The study reports no groundwater problems associated with the operation of the 2 694 documented Class III injection wells in the USA[16].

The US EPA set out the following requirements for operators of mineral extraction wells to mitigate against contamination to underground sources of drinking water (USDW) aquifers (US EPA text):

> Before commencing injection, operators must obtain an aquifer exemption[17] if they are injecting into a USDW (which is common in ISL uranium mining), or if the overlying aquifer may subside (which may happen in salt mining operations). The wells must be constructed with tubing made of materials that are appropriate for the injected fluids, which are cased and cemented to prevent the migration of fluids into a USDW. They must also provide financial assurance that resources exist to properly plug the wells when injection operations are complete. Operators must pressure test their wells prior to injection.
>
> During operation of the well, the operator must monitor injection pressure and flow rate, and they may not inject fluid between the outer-most casing and the well bore. Operators must also monitor USDWs below and above the mining interval if the well is injecting into a USDW of 3 000 ppm (parts per million) total dissolved solids (TDS) or less. Operators of salt solution mining wells must test the well casing for leaks at least once every 5 years.
>
> When injection operations are complete, Class III operators must properly close (plug and abandon) the wells.

7.2 Residual geothermal fluids

Reinjection of geothermal residual fluids started purely as a disposal method, but has more recently been recognized as an essential and important part of reservoir management. Reinjection serves not only to maintain reservoir pressure, but also to increase energy extraction efficiency over the life of the resource. Only a small part of the thermal energy in place in geothermal reservoirs can be recovered if reinjection is not applied. Thermal breakthrough has been observed in few geothermal reservoirs but has in all cases been found to be a manageable part of field operation. Silica scaling in surface equipment and injection wells is a delicate aspect of the reinjection process in most high-temperature geothermal fields, but silica scaling in the reservoir has not been considered a problem. Reinjection of low-enthalpy geothermal fluid into sandstone has not been successful for reasons that are poorly understood. The location of injection wells in relation to production wells influences the ratio of injected fluid recovered in production wells. For peripheral injection, about one third of the injected fluid is commonly recovered, whereas injection within the production area results in a higher ratio of recovered

[16] See EPA website for more information (http://water.epa.gov/type/groundwater/uic/class5/upload/study_uic-class5_classvstudy_fs_min_wells.pdf).

[17] See definition on EPA's website (http://water.epa.gov/type/groundwater/uic/glossary.cfm#exempted).

fluid. Subsidence is in general of small concern in geothermal operations, and micro-gravity has proved a valuable tool to estimate the recharge to geothermal reservoirs.

7.3 Hydrocarbons and fluids associated with oil and natural gas production

Injection wells are generally used for the underground storage of crude oil and liquid hydrocarbons in underground caverns – natural or man-made – and in reservoirs/aquifers. The wells are designed for both injection and removal of the stored hydrocarbons. The hydrocarbons are injected into the formation for storage and later pumped back out for processing and use. The underground reinjection of produced liquid hydrocarbons and natural gas can have different purposes: (i) provide industry with short-term deliverability during peak demand and/or set aside long term strategic reserves; (ii) increase production and prolong the life of oil-producing fields.

The use of underground caverns for the storage of petroleum and low boiling hydrocarbons such as ethylene, propane and butane has become a widespread practice in the petroleum industry. For this purpose, caverns formed by washing out salt from a thick rock salt bed have been particularly satisfactory, since the salt bed is substantially impervious to hydrocarbons, and leakage from the cavern through the adjacent formation does not occur. The use of washed out salt caverns is obviously limited, however, to areas in which suitable salt beds happen to occur. More recently, storage caverns have been prepared by mining out underground rock formations such as granite. While storage zones of this type are considerably cheaper than above ground storage tanks for storing low boiling hydrocarbons under pressure, they have not proved to be consistently successful due to leakage from the cavern through the adjacent rock. Rock beds often contain small channels through which the hydrocarbon can flow toward a zone of lower pressure. This not only causes loss of hydrocarbons but also may present a dangerous condition due to seepage of the hydrocarbon to the ground level.

Enhanced Oil Recovery (EOR) injection wells are used to increase production and prolong the life of oil-producing fields. Secondary recovery is an EOR process commonly referred to as water-flooding. In this process, salt water that was co-produced with oil and gas[18] is injected into the oil-producing formation to drive oil into pumping wells, resulting in the recovery of additional oil. Tertiary recovery is an EOR process that is used after secondary recovery methods become inefficient or uneconomical. Tertiary recovery methods include the injection of gas, water with special additives, and steam to maintain and extend oil production. These methods allow the maximum amount of the oil to be retrieved out of the subsurface[19].

Salt caverns or solution-mined caverns in salt formations are used for storing large volumes of liquid hydrocarbons and compressed natural gas. Salt properties, while usually advantageous for successful hydrocarbon storage cavern operations, can vary considerably both between dome and bedded salts and amongst bedded and dome formations. Salt property variations, inherent differences in caverns developed in bedded and dome formations, and the range in site-specific geological conditions strongly suggest effective regulatory attention. Solution-mined excavations in salt have been developed for temporary storage of a variety of hydrocarbons including crude oil, refined liquid hydrocarbons and, more recently, for compressed natural gas. The United States Strategic Petroleum Reserve, developed in the 1970s and 1980s, utilizes more than 50 underground caverns in salt to store nearly 600 million barrels of crude oil for emergency use. Solution-mined caverns in salt are also used by the private sector for temporary storage of crude oil. Solution-mined caverns in salt have been used on a limited basis for compressed natural gas since the early 1970s. However, the number of caverns planned or developed for compressed natural gas storage has risen rapidly in the last few years.

[18] When oil and gas are extracted, large amounts of brine are typically brought to the surface. Often saltier than seawater, this brine can also contain toxic metals and radioactive substances. It can be very damaging to the environment and public health if it is discharged to surface water or the land surface. By injecting the brine deep underground, surface contamination of soil and water is prevented. In the USA, when states began to implement rules preventing disposal of brine to surface water bodies and soils, injection became the preferred way to dispose of this waste fluid. All oil and gas producing states require the injection of brine into the originating formation or into formations that are similar to those from which it was extracted.

[19] Approximately 60 percent of the salt water produced with oil and gas onshore in the USA is injected into EOR wells.

7.4 Hydraulic fracturing

The geological evaluation of shale gas prospects identifies substantial volumes remaining within the original major source shale formations as shown on Figure 11. Most of the shale gas formations are of mid-Palaeozoic (Late Devonian) and Mesozoic geological age (ca < 375 to 69 Ma).

Figure 11: Major Worldwide shale gas prospects (from Canada Free Press quote source as 'No Hot Air, 2011').

The technique of hydraulic fracturing is used to increase or restore the rate at which fluids – such as oil or water – or natural gas can be produced from subterranean natural reservoirs, including unconventional reservoirs, such as shale rock or coal beds. Hydraulic fracturing enables the production of natural gas and oil from rock formations deep below the Earth's surface (generally 1 500-6 100 m). At such depth, there may not be sufficient porosity and permeability to allow natural gas and oil to flow from the rock into the wellbore at economic rates. Thus, creating conductive fractures in the rock is essential to extract gas from shale reservoirs because of the extremely low natural permeability of shale, which is measured in the microdarcy to nanodarcy range. Fractures provides a conductive path connecting a larger area of the reservoir to the well, thereby increasing the area from which natural gas and liquids can be recovered from the targeted formation.

While the main industrial use of hydraulic fracturing is in stimulating production from oil and gas wells, hydraulic fracturing is also applied to stimulating groundwater wells, preconditioning rock for caving or inducing rock to cave in mining, as a means of enhancing waste remediation processes (usually hydrocarbon waste or spills) or to dispose of waste by injection into suitable deep rock formations.

A hydraulic fracture is formed by pumping the fracturing fluid into the wellbore at a rate sufficient to increase the pressure downhole to a value in excess of the fracture gradient of the formation rock. The pressure causes the formation to crack, allowing the fracturing fluid to enter and extend the crack farther into the formation. To keep this fracture open after the injection stops, a solid "proppant" – commonly sieved round sand – is added to the fracture fluid. The propped hydraulic fracture then becomes a high permeability conduit through which the formation fluids can flow to the well.

The fluid injected into the rock is typically a slurry of water, proppants and chemical additives. Additionally, gels, foams and compressed gases, including nitrogen, carbon dioxide and air, can be injected. Various types of "proppant" (sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment) include silica sand, resin-coated sand and man-made ceramics. These vary depending on the type of permeability or grain strength needed. Sand containing naturally radioactive minerals is sometimes used so that the fracture trace along the wellbore can be measured. Chemical additives are applied to tailor the injected material to the specific geological situation, protect the well and improve its operation, though the injected fluid is approximately 99 percent water and 1 percent proppant, varying slightly based on the type of well.

The second stream of "unconventional natural gas resources" developments is the extraction of gas from coal beds (US EPA, 2002). Two methods of methane abstraction from coal beds are in use, the first extracts the gas from existing coal mine workings: This method is in use in Canada, China, Australia and in the USA where it forms some 10 percent of the total gas supply. The second method is termed underground coal gasification (UCG) and has been in study since the 1940s in Europe and the USA, and recently in Australia. The method applies hydraulic fracturing of the coal beds in a similar manner to that used for gas shales extraction. The only commercial operation is in Uzbekistan. The method and potential impact on freshwater aquifers is set out by the US EPA (2004).

7.5 Carbon dioxide capture and storage

Carbon capture and sequestration (CCS) is the process of storing carbon underground to curb accumulation of carbon dioxide in the atmosphere[20]. It is undertaken because natural sinks of carbon (forests, oceans and soils) are considered unable to accommodate the increasing amounts of carbon dioxide emitted by humans, with consequences in terms of climate change.

The general public is less informed about CCS than about nuclear waste, but when concrete projects are considered there is often public opposition against it (so-called 'NIMBY effect'). This opposition is based on perceived health risks for the population in the neighbourhood if stored carbon dioxide would leak to from the repository (e.g. empty oil or gas reservoirs) to the surface. Although CO_2 is a standard compound of the air (0.04 percent by volume), it becomes poisonous at large concentrations. That such concentrations are not illusory in the case of leaks – because of its relatively high density – is demonstrated by the famous example of suffocating CO_2 concentrations (in this case of a natural origin) observed in the Grotta de Cani near Naples, mentioned already by Plinius and described in detail in Athanasius Kircher's Mundus Subterraneus (1664). More recent examples of such hazards are the death of 1 700 people in 1986 resulting from release of CO_2 from the Nyos Lake in Cameroun and the incident in 2008 in Mönchengladbach (Germany) where CO_2 escaped from a defective fire extinction installation, causing illness of 107 people.

Major geological storage of CO_2 is ongoing in three industrial-scale projects (projects in the order of 1 $MtCO_2$ /yr or more): the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. About 3-4 $MtCO_2$ that would otherwise be released to the atmosphere are captured and stored annually in geological formations.

Many storage sites are far from large emission sources. Coupled with the fact that long-range intercontinental transportation of CO_2 would incur significant additional cost, this means that the economic storage potential is country- and region-specific and smaller than the total geologic storage potential. However, in most world regions, storage capacities do not pose a constraint for widespread CCS use for decades to come. At this stage, the total cost of CCS could range from 50 to 100 USD per ton of CO_2. This could drop significantly in future. In most cases, using CCS would cost 25-50 USD per ton of CO_2 by 2030, compared to the same process without CCS. Certain early opportunities exist with substantially lower cost, but their potential is limited. The cost of CO_2 storage depends on the characteristics of the site, its location and the method of injection chosen. In general, at around 1-2 USD per ton of CO_2, storage costs are marginal compared to capture and transportation costs. Revenues from using CO_2 to enhance oil production could be substantial (up to 55 USD/tCO_2) and could enable the cost of CCS to be offset. However, such potential is highly site-specific and would not apply to most CCS projects. Longer-term costs for monitoring and verification of storage sites are of secondary importance. Using CCS with new coal- and gas-fired power plants would increase electricity production costs by 2-3 US cents/kWh. By 2030, CCS cost could fall to 1-2 US cents per kWh (including capture, transportation and storage).

CO_2 Injection Technology, that is the injection of CO_2 in deep geological formations, involves many of the same technologies that have been developed in the oil and gas exploration and production industry. Well-drilling technology, injection technology, computer simulation of storage reservoir dynamics and monitoring methods from existing applications are being developed further for design and operation of geological storage. CO_2 storage in hydrocarbon reservoirs or deep saline formations is generally expected to take place at depths below 800 m, where the ambient pressures and temperatures will usually result in CO_2 being in a liquid or supercritical

[20] See definition of carbon dioxide and atmosphere at http://www.greenfacts.org/glossary/abc/carbon-dioxide.htm http://www.greenfacts.org/glossary/abc/atmosphere.htm.

state. Under these conditions, the density of CO_2 will range from 50 to 80 percent of the density of water. This is close to the density of some crude oils, resulting in buoyant forces that tend to drive CO_2 upwards. Consequently, a well-sealed cap rock over the selected storage reservoir is important to ensure that CO_2 remains trapped underground. When injected underground, the CO_2 compresses and fills the pore space by partially displacing the fluids that are already present (the '*in situ* fluids'). In oil and gas reservoirs, the displacement of *in situ* fluids by injected CO_2 can result in most of the pore volume being available for CO_2 storage. In saline formations, estimates of potential storage volume are lower, ranging from as low as a few percent to over 30 percent of the total rock volume.

The initial perceived risks associated with CO_2 sequestration are shown on Table 4. Some historic incidents linked to the escape of injected CO_2 used for enhanced oil recovery have occurred and frequent parallels of the dangers are drawn with the CO_2 cloud released from Lake Nyos in NW Cameroon in 1986 as the result of a local tremor and landslip. For similar reasons, CO_2 sequestration sites should not be located in tectonically active or volcanic areas where caprock damage and rapid pressure and temperature changes could disrupt the equilibrium of the CO_2 density and solubility: this would create the risk of uncontrolled, rapid migration and escape of stored CO_2. Periodic measurements for CO_2 in the soil gas profile, included in the monitoring programme may identify leakage.

Table 4: Generalised risks associated with geological sequestration of CO_2 (redrawn and adapted from Chadwick et al.*, 2008)*

Risk of Geological Storage of CO_2

Local Risks | Global Risk

CO_2 in atmosphere	Deep sequestrated dissolved CO_2	Physical and chemical risks	Release of CO_2 into the atmosphere
Human illness of suffocation	Mobilisation of metals and contamination	Ground disturbance	
CO_2 in soils above water table	Contamination of USDW aquifers	Contamination of displaced USDWs	
Damage of destruction of vegetation and fauna.	Interference of deep ecosystems	Damage to hydrocarbon and other resources	

7.6 Governance issues

Hydraulic fracturing has become a contentious environmental and health issue with France banning the practice and a moratorium in place in New South Wales (Australia), Quebec (Canada) and some of the states of the USA. Concerns about environmental and human health effects associated with hydraulic fracturing include the contamination of groundwater, risks to air quality, the migration of gases and hydraulic fracturing chemicals to the surface, and the potential mishandling of waste. The potential costs associated with possible environmental clean-up processes, loss of land value, as well as human and animal health concerns are as yet undetermined. Given the intensity of many shale gas wells (Figure 12), it is hard to dismiss public concern over the chemical composition and fate of the hydraulic fluids after the fracturing is completed (US Secretary of Energy Advisory Board, 2011). A comprehensive and well reasoned industry effort to educate the population (King, 2012) recognizes and addresses much of the furore over hydraulic fracturing.

Building on this concern the US EPA is drafting regulations covering water use, chemical disclosures, wastewater discharges and injection wells to effectively sidestep the terms of the 2005 Energy Policy Act and bring in appropriate guidance and rules. However, given the dichotomy between State and Federal legislative primacy, the introduction of a new governance regime in the USA is under discussion and remains to be settled (Pardo, 2012).

In Europe, a group of environmental and health NGOs set out a list of very similar doubts and questions that are largely based on the claimed problem areas cited in the USA (EEB, 2012): the group calls for a moratorium on all developments until their questions are answered.

Figure 12: Dense concentration of well sites: shale gas development in Pervis County, Mississippi, USA (Google Earth Image).

Two reports commissioned by the European Parliament (EU, 2011; Philippe & Partners, 2011) present slightly contradictory views on shale gas developments. The first (EU, 2011) notes the lack of a European Mining Law and the absence of an analysis of the available European regulatory framework covering shale gas developments: While it notes that there are probably gaps in the regulatory framework, when compared with other industrial developments, it concludes the current environmental impact assessment thresholds are probably higher than strictly necessary. The report concludes that the assessments should concentrate on a life cycle assessment (LCA) of the developments as when examined in detail each aspect of the life cycle is adequately understood and covered by appropriate existing legislation, if the rules are properly enforced. In particular they quote the EU Groundwater, Water Framework and EIA Directives and recommend that an EU extractive industries directive is developed that specifically includes shale gas developments. The second EU Commission report published in 2012 (Philippe & Partners, 2011), although limited to studies in Poland, France, Germany and Sweden, recognizes that shale gas developments employ some relatively new technology but considers it does not immediately need specific new legislation and concludes that no further EU or national regulation of shale gas development is necessary. The report contends that the existing water framework, groundwater and mining waste directives cover any associated environmental risks while the EU REACH Directive[21] covers the use of hydraulic fracturing fluid additives. However, the report further concludes that this situation should be kept under review as the scale of shale gas development grows. In May 2012, the UK approved shale gas investigations in northwest England but stipulated the development must include carbon sequestration.

Finally, the 2012 draft New South Wales Aquifer Interference Policy (NSW Government, 2012) adopts a risk management approach that requires investigations of sufficient level to fully assess the risks associated with a development.

[21] Registration, Evaluation, Authorisation and Restriction of Chemicals EU Directive available form: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:en:PDF.

8. Construction into the Underground Space

Traditional underground constructions, such as foundations of buildings, cellars, wells and infiltration galleries, have been practiced already for many centuries. Cave dwellings have been in use in history in some areas of the world (e.g. in the French Alps, Pindus mountains in Greece, Cappadocia region in Turkey), but nowadays only on the Chinese Loess Plateau (Xinjiang) a very significant number of people still lives in caves (40 million people). From the late 19th century onwards, however, construction into the subsurface space has become much more intensive than ever before, in particular for purposes of storage and logistics. The motivation behind constructing underground is to a large extent the lack of space at land surface and the desire to protect environmental quality above the ground. In addition, underground space often offers a number of advantages in regard of the envisaged functions, such as a rather constant temperature and protection against certain external interferences and risks.

8.1 Categories of construction

Pipelines, sewerage systems and cables

Pipelines are commonly used for transport and/or distribution of fluids, in particular water, gas and oil. In densely populated areas they are usually buried, at shallow depth and above the groundwater table. Leaks constitute potential pollution risks for groundwater, although distributed drinking water is generally harmless. Leaking sewerage systems, mostly buried as well at shallow depth, present a much greater pollution risk (leaks are frequent and sewage contains pollutants). Cables for electricity and communication (telephone, Internet, TV, etc.) can be found at similar depths, but these do not constitute significant pollution risks to groundwater.

Traffic (tunnels and underground railways)

Tunnels allow traffic to pass an obstacle (mountain, river, canal or build-up area) or to cross a railway or road safely. Particularly dense tunnel systems are formed by urban underground rail networks. Since the middle of the 19th century, underground railways (known as: Underground, Métro, U-Bahn, Subway, etc.) have been constructed in urban agglomerations. The oldest ones are in London (1863), Istanbul (1889), Budapest (1896), Glasgow (1896), Boston (1897), Chicago (1897), Paris (1900), Wuppertal (1901), Berlin (1902), New York (1904), Hamburg (1912), Buenos Aires (1913), Philadelphia (1914) and Madrid (1919). At present (2011), there are 146 urban underground railway networks in the world, scattered over 54 countries.

If tunnels – as stand-alone constructions or as components of underground railway networks – are constructed below the water table, then the groundwater regime may be significantly disturbed during construction (e.g. by artificial well-point drainage) and land subsidence may occur by compaction of compressible layers. A recent example is provided by the North-South Metro Line construction project in Amsterdam, where leaking sheet pile walls caused groundwater to enter the tunnel under construction, resulting in damage to monumental historical buildings built in a zone of compressible formations (period 2004-2008). A rather similar groundwater-related problem during the U-Bahn construction in Germany caused, in 2009, the collapse of the famous Historical Archive of the city of Cologne – as sand under the building was removed by drained groundwater – with loss of human lives and many irreplaceable historical documents. After finalizing tunnel projects, the tunnels may have a permanent influence on shallow groundwater regimes, due to the presence of cofferdams, pile dams, immersed tubes, grouting, slurry walls or other obstructions to groundwater flow. In addition, some tunnels may form preferential locations for the entry of pollutants into groundwater systems.

Underground car parks and other underground constructions

There is a tendency to locate new car parks underground, in order to save space above the ground in urban areas. During construction, conditions and potential problems are similar to those of tunnel construction. After completion, car parks constructed under the water table may need permanent artificial drainage, in order to ensure the car park's stability. The same applies to subsurface urban areas with shopping centres, offices and storage facilities that gradually are developing in various metropolitan areas (e.g. in Montréal since 1962; nowadays also in Washington DC, Kansas, Seoul, Tokyo and Paris).

In several countries, ideas are being developed for a more systematic and intensive approach to using the underground space for buildings with commercial or public functions. Impressive open spaces in the shallow subsurface do exist already in some cities – such as Paris, Jerusalem and Naples – because this is where for centuries building materials have been extracted for local construction. These spaces are ready for getting a function.

8.2 Governance aspects

Probably in most countries regulations do exist regarding different categories of underground constructions. However, poor enforcement, budgetary problems and unexpected problems sometimes may lead to poor compliance with these regulations, such as happened in the Amsterdam North-South Metro Line project, where local politicians ignored technical advice and negative test results in order to keep their prestigious project going. Several classes of underground constructions require permanent monitoring to ensure that interactions with subsurface formations and groundwater remain within safety limits. This particularly applies to the construction of sewerage systems at depth.

Although underground constructing may affect groundwater systems, it seems that the subject is rarely included in groundwater management plans and that groundwater resources managers are rarely involved in regulations and decision-making on underground construction.

9. The Planning Process and Aquifer Use

Planning processes related to the underground can take many forms, depending on the chosen scope, focus, approach and other factors. In the most concrete form, planning processes are related to a single technical project activity, e.g. the construction of a well for an individual farmer, the development of an underground waste disposal site, the exploitation of a mine, the construction of a tunnel or the installation of a sewerage system. Although the degree of complexity may vary enormously, the planning activity in all these cases focuses on successful completion of a technical project and includes a breakdown and description of single project activities, allocation of tasks and responsibilities, cost estimates, time schedule and the like. The presence and properties of the subsurface are taken for granted; investigating the subsurface usually receives no more attention than needed for a proper design of the envisaged technical works and for complying with formal obligations (e.g. an environmental impact assessment). This is the oldest and most easily understood type of planning: straightforward and focused on tangible outcomes, according to a clear time-path.

At the other side of the spectrum we may observe forms of comprehensive integrated planning. They do not focus on single technical activities, but either on a certain sector (e.g. water supply or waste management) or even on a certain natural resource (integrated water resources management, land use management, subsurface management). Integrated planning takes a broader perspective and especially the latter category – natural resources management – focuses on high-level objectives (e.g. sustainability, macro-economic impact, equitable distribution of benefits, environmental protection) rather than on short-term technical outputs. Single technical activities may be included as means to achieve these objectives, together with non-technical measures that intend to influence people’s behaviour.

9.1 Current practices

Single-project planning always emerges when subsurface works have to be carried out. In most low-income countries, this is still the predominant form of planning, not – or only weakly – linked to any form of more integrated planning. Absence of significant integrated planning is in the first place explained by scarcity of means (budgets, expertise, institutional infrastructure), but also because its potential benefits are not yet widely understood and/or because countries cannot afford (financially or politically) to adopt the precautionary principle[22]. In other countries, mostly post-industrial ones, over time a tendency can be observed towards integrated planning, to which single-project planning is made subordinate. In a first phase often a sector-oriented integrated planning was adopted (e.g. public water supply of a town or region), which allowed to select an optimal mix of components to achieve the operational objectives of the entire sector. After having experienced the interdependency between sectors and the degradation of certain functions of the underground (e.g. groundwater depletion or groundwater pollution), area-specific resources planning (e.g. a water resources management plan) came into vogue in certain countries or states. They constitute a general framework specifying measures to be implemented and criteria for judging whether proposed technical activities should be allowed or not, based on the precautionary principle.

9.2 Looking towards the future

Human activities related to the underground – be it for abstraction of natural resources, land use, storage of waste or energy, underground construction or other purposes – will steadily become more intensive in the future. Hence, the interferences between the different activities are intensifying accordingly, externalities are becoming more pronounced and irreversible degradation of the natural resources is likely to occur. Not only do these trends legitimize government interventions on the basis of a natural resources management plan, they strongly motivate them as well, because without such interventions societal opportunities may be lost and natural resources irreversibly damaged. Here lies an enormous challenge for countries where integrated natural resources management (in particular IWRM) is not yet common practice. Even where integrated management is practiced, it is at present usually still separate for different policy fields: water resources management, mining, land use planning, waste disposal, use of shallow underground space and so on. Further development of the

[22] The precautionary principle states that if an action or policy has a suspected risk of causing harm to the public or the environment, the burden of proof that it is *not* harmful falls on those taking the action.

integrated management approach to some of these fields (e.g. use of shallow underground space) and making the management plans in different policy fields fully consistent are the next challenges.

Part 2 Diagnostic: including constraints/barriers, potentials, and safety issues

10. Constraints and Opportunities

Many developments outlined in the preceding sections are in the energy sector or mineral production and processing sectors and, given the high energy usage in mining and processing, they are basically high-cost integrated projects. The preceding sections have also included considerable diagnostic analysis and examples of how concerns over groundwater availability and quality lead to the introduction of controlling legislation.
In Europe and North America, the public campaigns are generally strong enough to exert pressure on politicians to implement environmental legislation. Elsewhere this may not be the case and many subsurface developments have been undertaken by commercial enterprises under an initially weak or non-existent regulatory regime. For instance, China's current production of rare earth elements has a high environmental impact. In Europe and North America such mining practices would require implementing environmental measures that would result in a high production cost.

Under centralized planned economies, the state has controlled and developed both the energy and mining sectors.

Although common to all scientific and governance fields, the need to develop an internationally accepted dictionary of definitions and a standardized system of measurement units will contribute to the transfer of knowledge. It may also reduce or eliminate dangerous or costly of embarrassing mistakes as seen with the crash of the Mars Lander Mission (North Carolina EPA, 2010).

10.1 Barriers and constraints in adopting an orderly path

Lack of data/information and insufficient knowledge of relevant processes
An orderly governance process regarding the exploitation of groundwater and other uses of the underground requires in the first place sufficient information on the subsurface down to relevant depths. Knowledge of the underground is in practice usually based on very limited data, based on which an image is interpreted that is subject to rather large uncertainties. Due to these uncertainties there is significant risk in all subsurface activities (especially the very deep ones), but reducing risk by collecting additional field data is very expensive and often considered not affordable. Since human interest and human behaviour are part and parcel of using and governing the subsurface and its resources, it is necessary to have sufficient information on the socio-economic and political settings as well. Although more visible than the underground, these aspects are often overlooked.

Apart from data and information, it is also necessary to have good knowledge on the relevant processes. Only then it is possible to make reasonable predictions of the impact of any set of measures considered. In particular the assumptions on human behaviour are often overly simplistic. In many cases, the content of governance strategies and the required overall vision are limited by insufficient data, information and knowledge.

Insufficient institutional capacity and mandate to organize an orderly path
Good governance is not spontaneously emerging. It needs continuously initiatives to be taken and activities to be carried out by key partners in the process. Sufficiently strong specialized institutions, with proper mandate and recognized by stakeholders, are indispensable to take the lead in planning and management. Often they are missing, not strong enough or not sufficiently dedicated.

Lack of funds
Sufficient funds are needed to enable the activities required to ensure good governance. Often such funds are not allocated, or not available at the appropriate moment.

Inadequate legislation and regulatory frameworks
Most countries probably have a law on mining activities, and water laws have become rather common as well. For some underground activities, however, specialized laws and regulations may be missing, which may create a vacuum between government agencies and private parties, with the risk of conflicts or issues not properly

addressed. In addition, existing legislation related to different aspects of the underground may be partly conflicting or confusing.

Insufficient political support or vision
The benefits of governing underground natural resources are often not properly understood by politicians, or the subject may not fit into their agendas. Rather than being involved in activities of restrictive nature politicians may have preference for supporting activities that give them more positive visibility on the short term. Nevertheless, political support is essential to create conditions for the development governance processes by providing funding, legislation, institutions and positive messages to stakeholders.

Insufficient government power
Public authorities must be endowed with adequate powers to ensure regulation and enforcement. If governments have very limited power in the area concerned, then they are incapable to play an adequate role in governing the underground resources. In most cases, this will shut the door to the development of good governance of subsurface resources.

Lack of transparency and communication on planning, decision-making and implementation
Once initiatives are taken for resources management, the population of the area concerned as well as organizations involved in certain related activities have to cooperate and comply with regulations. Often insufficient attention is paid to informing the public on the planning, decision-making and implementation processes, with the result that anticipated cooperation and compliance are not forthcoming.

Insufficient involvement of relevant stakeholders
This is related to the previous constraint. Under given circumstances, certain groups of stakeholders expect to play a certain role in the government process. If they are ignored by dominant parties (e.g. a government agency), then their views and preferences are not incorporated and they may become frustrated, non-cooperative or even inclined to sabotage.

Lack of mutual confidence between key actors (including lack of balance of power)
Parties involved have often a negative image of other parties, e.g. by considering governmental agencies arrogant or corrupt, technical scientists as not having contact with the 'real world' and local people as not clever enough to decide about their own future. As long as such negative perceptions remain, smooth and successful cooperation may be hindered.

No consensus on facts and on predictions
Given the usual scarcity of information, interpretations and uncertainty play a role. Hence, differences of opinion on the factual situation and on predicted futures may easily arise. Sometimes, such differences of opinions are influenced by the different stakes of the parties involved. If consensus is completely lacking, then any actions to move forward may come to a standstill.

No consensus on preferences or on allowable risks (conflicts of interest)
Conflicts of interests are always present in complex situations where 'common pool' resources are being used and externalities are created. Under favourable conditions, ways will be found for conflict resolution and for negotiating a compromise. If this is not possible along formal lines, then groups of activists may organize pressure in order to call attention and support for their point of view, or groups may boycott the governance process or the decisions taken.

Rapidly changing boundary conditions
Governance processes have their own pace but, because of so many parties involved, they proceed usually rather slowly. Consequently, before plans have been implemented fully, they may be outdated already because of rapid changes of boundary conditions (demography, climate change, economic situation, etc.) departing from the assumptions made during plan development. This is to some extent the fate of each planning activity. It should be taken into account by incorporating sufficient flexibility for making adjustments to measures when required.

The list of barriers, constraints and other complicating factors presented above is not exhaustive, but includes a number of important items. Roughly, they can be subdivided into two groups: the first one related to enabling conditions for developing government; the second one to how to play the game. As can be observed, there are clusters of mutually dependent items. A perfect world where all these constraints and barriers are absent does not exist. People have to be creative to adopt approaches where existing barriers and constraints are not paralyzing the process or even can be reduced. One of the key conditions that have to be addressed is creating sufficient political and public support for governing the underground resources. This will be the key to reducing all other constraints and pave the road towards acquiring the means needed and to forging cooperation between the main actors.

10.2 Scope for securing social and environmental benefits through smarter regulation of the underground space

> Geosciences are hard sciences, valid at any time and place. Law sciences are soft ones, varying from country to country, from time to time. They must adapt to a sustainable use of underground space. (Duffaut, 2009)

Increasingly underground space is seen as playing a more significant role in the cities of the future, given the huge social and environmental costs of surface development. The world's subsurface space is already used in a variety of ways, ranging from occupancy to disposal and bulk storage of materials and fuels. In the future, it is likely that it will be put to further use in response to trends in technology, resource supply and demand, socioeconomics and geopolitics. Future uses are likely to be in the area of increasing occupancy (both commercial and residential), the secure storage of documents and data, the storage of carbon dioxide for carbon abatement, natural gas, compressed air stores of energy from traditional and renewable sources, the use of underground heat in buildings and the deep geological disposal of wastes, including radioactive ones.

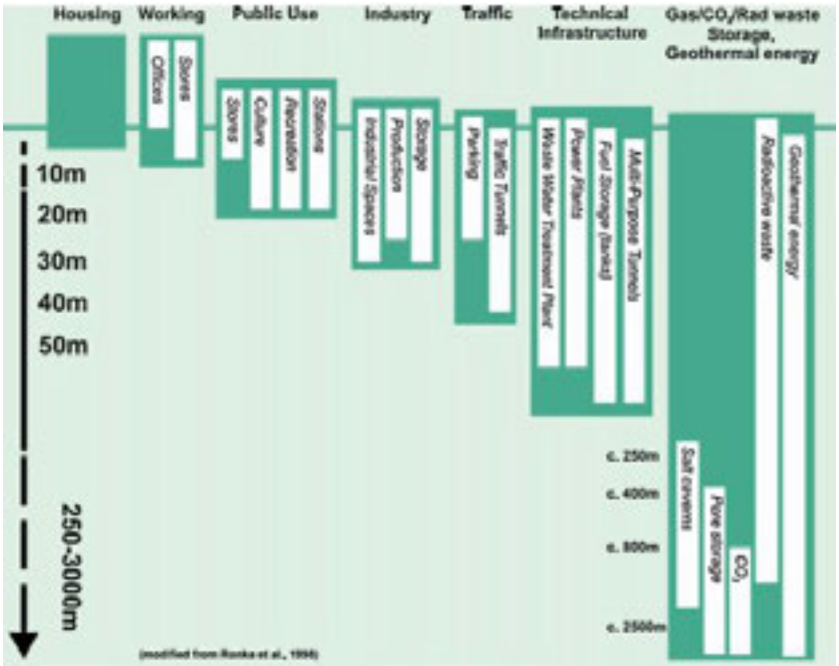


Figure 13: Feasible depth ranges for underground activities (based upon Ronka et al., 1998).

Worldwide, the last two decades have seen rapid development in the utilization of underground space and it appears that more use will be made for storage purposes, particularly for energy, and more of our lives are likely to be spent underground as shopping, recreation and even accommodation will be found in the subsurface. Because of its multiple uses and of the interdependencies of those uses, the subsurface will be more crowded, which will necessitate more integrated and comprehensive planning, regulation and monitoring. This will require more geological research to inform policy and regulation and to gain public engagement and acceptance. The risk involved in the various uses of underground space will have to be assessed. For example, a survey at the European Union (EU) member state level indicates that regulation and research on the potential impacts of Underground Thermal Energy Storage (UTES) on groundwater resources and the subsurface environment often lag behind the technological development of an ever-growing demand for this renewable energy source. The lack of a clear and scientifically underpinned risk management strategy implies that potentially unwanted risks might be taken at vulnerable locations such as near well fields used for drinking water production, whereas at other sites, the application of UTES is avoided without proper reasons.

The lateral expansion and increase in population that have characterized urban growth and development patterns of the last few decades have produced cities that are often inconsistent with the principles of sustainable development. Due to the high rate of global urbanization, problems such as greater traffic congestion, higher levels of air pollution, lack of green space and insufficient water supplies not only affect the cities in which they occur, but extend around the world. Cities that optimize the use of the third dimension are seen as a possible path to sustainable urban form. The urban underground possesses a large untapped potential that, if properly managed and exploited, would contribute significantly to the sustainable development of cities[23]. Traditionally, planning of underground works is done on a single-project basis with little consideration of other potential uses. This approach often produces interference between uses (e.g. road tunnels interfering with geothermal structures), causes negative environmental impacts (e.g. groundwater contamination) and restricts innovative opportunities for sustainable development (e.g. using waste heat from metro lines for heating buildings).

Regulating the utilization of underground space and resources
The challenge ahead will be the definition of policies, legislation and science-based methodologies to regulate the multiple uses of the subsurface space taking into account all the underground space and resources simultaneously. For projects of national importance, including storage, public opinion is to be taken into due consideration to lessen the effect of local opposition relative to the 'national need'.

Subsurface use is restrained by sets of laws and regulations firstly devised for constructions over the surface. The extension of private property to the centre of the Earth, deriving from the Roman legal tradition, is today counterproductive and is in fact often limited in modern legislation. The subsurface of a city might be a Public-Private Partnership like the common parts in a condominium. Town planning must install all utilities inside common galleries. Transportation needs should make a better use of underground roads and railways. Up to now, transportation of freight and goods inside cities appears a severely underrated problem.

10.3 Reconciling the role of the private sector and the public interest

In common with the regulation of most modern developments, establishing appropriate legislative controls usually only follows after noticeable adverse impacts have already occurred.

The current arguments over the classification of hydraulic fracturing of wells during shale gas developments show how lobbying by vested interests is designed to sway legislation in their favour. However, this can be against the public interest when the result is a blanket approval for totally uncontrolled developments: the history of international mineral exploration and development corporations rightly leaves them open to the public view that the companies have generally behaved in a cavalier way when not held into account by strong local regulation. In the past, the disregard of international corporations can be considered to have challenged the primacy of the host country. Recent examples are the dumping of toxic crude oil waste in Côte d'Ivoire by Trafigura and similar dumping of radioactive material in Somalia. In the USA, lead contamination caused by the flooding of the underground workings around the Picher Mines in Oklahoma was found to be so toxic that the US EPA deemed clean-up was impractical: a federal buy-out scheme was put in place and the town and surrounding mining area was completely evacuated in 2009. All these incidents posed an immediate threat to the local and regional groundwater sources.

[23] The use of the four principal resources of urban underground (space, groundwater, geothermal energy and geo-materials) can be optimized to help create environmentally, socially and economically desirable urban settings. For instance: space can be used for concentrating urban infrastructure and facilities, as well as housing, parking facilities and transportation tunnels; energy from geothermal sources and thermal energy stored in the underground can be used for heating and cooling buildings, thereby reducing CO_2 emissions; groundwater can be used for drinking water supply; and geomaterials from urban excavation can be used within the city to minimize long-distance conveyance.

Establishing robust legislation to protect public interest in the poorer countries, where enforcement and regulations lag behind those of the more economically advanced nations, calls the setting and policing of internationally recognized laws. The EU industrial directives provide examples of appropriate regulation.

10.4 Conditions for 'acceptable' development of deep groundwater and planned depletion

The dominant abstraction from deep aquifers is generally performed by large-scale irrigation projects in areas with a low population density. In many cases, the developed aquifers receive very little modern recharge and the abstraction takes groundwater from storage. In most cases, the decision to continue withdrawing groundwater from storage is based on political judgement that in turn relies on a reasoned technical assessment of the scale of the resource. In the case of the High Plains Aquifer in the USA, an arbitrary limit has been set in Texas and in other states based on retaining 50 percent of the existing groundwater in storage at a certain date in the future (usually 2050). However, a huge depth of scientific study is needed to judge if this large-scale High Plains Aquifer abstraction is acceptable, and ultimately the verification of the success of these management plans, or otherwise, will depend on a well-funded and assiduous long-term monitoring programme.

The core of groundwater science evolved from legal conflicts that arose from the practice known in the early oilfield developments as "offsetting". The oil producers in the USA resolved the issue with the introduction of the unitization model (Section 4.1) and it has been suggested that a similar model could be used to replace the abstraction right models that are based on the concept of groundwater as a common-pooled resource. Jarvis (2011) compares the basic elements of the two models as shown before in Table 2 (see Chapter 4). The subtle difference between the unitization development model and the common-pooled resource approach is that the unitization model is centred on managing the *in-situ* pore fluids to maximise their recovery for the benefit of all developers whereas the common-pooled model concentrates on the distribution of groundwater abstraction rights.

A successful unitization model for an oilfield development requires a number of conditions to be satisfied and Kumar (2007) lists the four main types of unitization models as (text from Jarvis, 2011):

- Voluntary units: agreements among interested parties that can be undertaken for exploration or conservation;
- Compulsory or conservation units: a high level of knowledge of physical characteristics of the "pool" is required for conservation;
- Geographic units: typically applied where poor well-control precludes defining boundaries of productivity, or in areas of complex geology;
- Geologic units: typically applied based on geology, productive area, lease position, precedent in a field, producing horizon or trend or economics.

The use of unitization models can be considered as appropriate for the governance of planned depletion of deep-seated non-renewable aquifer resources.
While there are no published examples of unitization being used to regulate groundwater abstraction, Jarvis (2011) reports that the principles are being applied in Utah (USA) where landowners, facing a State enforced reduction in groundwater abstraction, voluntarily pooled their groundwater abstraction rights and formed a "unit", the Escalante Valley Water Users Association, to share the reduction in available groundwater resource. A similar scheme incorporating many of the features of the oilfield models was also initiated in the over-stressed groundwater basins of the Milford Flat area in western Utah.

10.5 Conditions for regulated use of deep aquifer stores and repositories

The four main applications of deep drilling that impact on groundwater are water supply, shale gas, CO_2 sequestration and geothermal development. In many cases the hunt for new sources of freshwater will affect the stored groundwater volume and introduce dynamics.

As with the large regional aquifer developments, the shale gas and CO_2 sequestration projects target formations are located in the deep sedimentary basins. However, looking at Figure 12 one must pose the question of what happens when such a shale gas development is depleted and scheduled for abandonment, given the cited USD 0.5 million (at 2012 prices) for the plugging of each well to which must be added the clean-up and disposal of the storage ponds and foundation works. It is highly unlikely that the system operators will be – or willing to be – in a financial position to meet these costs unless some form of escrow account is set up during the operational life of the scheme. (The same goes for all underground and open cast extractive mineral developments).

As also previously indicated, recommendations have been made for the EU to develop an extractive industry directive to control such developments in the 23 EU States. Developing controls for deep wells for such a directive will undoubtedly draw heavily on the US EPA injection-well classification (Appendix 1). In doing this the EU directive will be in a position to tidy-up the apparent discrepancies with this classification of the hydraulic fracturing wells and to distinguish between the deep and shallow non-toxic waste disposal wells currently included in the same class under the US EPA Underground Injection Controls.

It is felt that the United Nations Environmental Programme (UNEP) and a new EU extractive industry directive could prompt the development of a set of internationally accepted regulations.

Part 3 : Prospects

11. Future Role of Technology in Managing the Underground Space

Consideration of the range of foreseeable activities set out in Figure 13 shows that the majority of developments lies within the capabilities of current technology, and certainly more efficient ways will be found to undertake underground developments.

Apart from the very high costs involved, the hyper-cautious approach to implementing secure and permanent high-level radioactive waste storage is largely driven by a lack of confidence in the known technology as set out by Comby (2005). From the tunnelling aspects, technology has enabled several undersea crossings to be constructed and accepted for everyday use: notably the 53.8 km Seikan Tunnel between the Japanese islands of Honshu and Hokkaido. This tunnel reaches a maximum of 140 m below the seabed and was constructed through very difficult geological ground conditions. There are many other land tunnels with the longest being the 57.1 km Gotthard Base East Tunnel that is scheduled to open in 2016 and cuts through the complex geology of the Alps. The principal technical concern with radioactive waste disposal sites is leakage to surface and groundwater systems either through corrosion of the storage capsules or damage caused by seismic activity. Both these risks have been addressed and accommodated in the construction of these tunnels.

With the 2012 linkage established in the UK between shale gas abstraction and CO_2 sequestration, the future of these two developments can be expected to accelerate as the demand for energy and gas continues to grow. However, this growth can be expected to bring further developments in managing the underground space. The first developments are likely to be the expanded use of injection wells to create saline-intrusion barriers and the possible use for large-scale subsidence control. The creation of saline barriers is already in place for the protection of concrete foundations from salt corrosion and Poland *el al.* (1999) report on the large-scale, long-term use of treated freshwater-injection wells to create a hydraulic barrier (or pressure ridge) to prevent saline intrusion in southern California.

The small-scale use of injection wells for subsidence control to compensate for settlement caused by the construction of tunnels and highways in Oregon is recorded in the US EPA (1999) paper on Class V UIC wells. However, the main cause of widespread land subsidence is formation compaction due to the abstraction of groundwater from confined aquifers: Figure 14 shows the extent of this form of subsidence recorded in the USA.

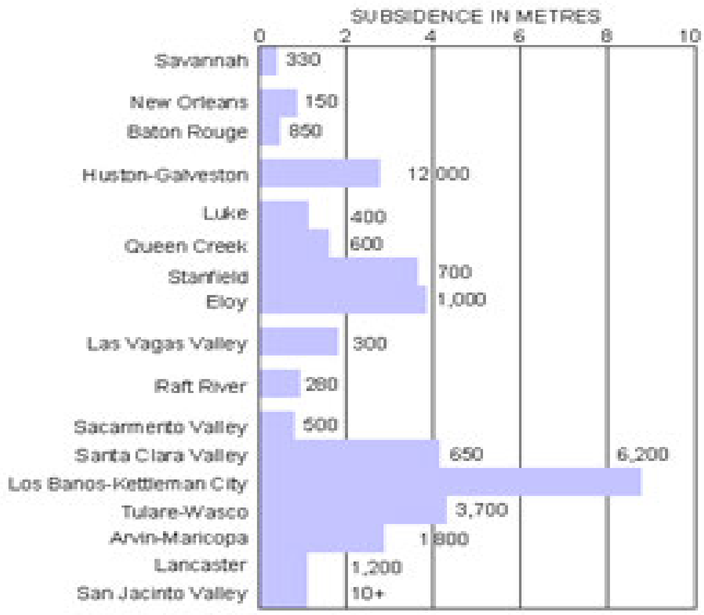


Figure 14: Land subsidence due to groundwater abstraction in the USA. Numbers refer to area of basin in km² (Redrawn from UNESCO, 2000).

Outside the USA, Poland *et al.* (1999) describe various schemes, test and pilot schemes to re-pressurise the confined aquifer responsible for the subsidence in Shanghai, China, Venice, Italy and Niigata, Japan. The increasing frequency of flooding in Bangkok, Thailand has brought the subject of subsidence control and reversal into focus. The nature of the poorly consolidated sedimentary formations in the Lower Chao Phraya Basin and the sheer number of existing water wells into all aquifer horizons suggests that achieving sufficient hydraulic sealing of the aquifers may not be possible.

In other areas, there could be a possibility of pressurising the shale horizons using the same technology adopted for shale gas abstraction and CO_2 sequestration. Given a 5-percent shale porosity, the volumes of injected water to achieve over-pressurisation and hence land uplift will be less than that required to achieve the same effect in a more porous aquifer. It is likely that such sites exist in the Mississippi Delta. Precision Global Positioning System (GPS) level measurements are now available to test the effectiveness of subsidence-control pilot schemes.

A major constraint to the use of injection wells for any purpose is the role of bacteria and biofouling in reducing the permeability of the formations around the wall of the injection well. While the use of biocides is accepted for the development of shale-gas wells, specific studies will be needed to establish appropriate sterilization processes where drinking water aquifers are involved. Indeed the whole subject of underground bacteriological action above and below the water table probably represents a major area for future investigation and research beyond its common use for bioremediation of contamination plumes. The contribution of bacteria to the rock weathering process is becoming increasingly recognized, and the prospect of identifying biological/viral activity and zoning in aquifers is beginning to be investigated for both the mineral recovery and groundwater quality studies (Eydal, 2009). Current research[24] shows the long-term presence (at least 25 Ma) of viral and bacterial lifeforms similar to those found around the mid-oceanic rift "black-smoker" volcanic plumes in groundwater contained in granites 3 km below ground, with radioactive decay and sulphur providing the energy sources (Eydal, 2009).

In the near term, rare earth elements will provide the major impetus for new mining and processing projects and these developments will create further demands for groundwater supplies, energy and pose additional environmental threats in the geographical areas as shown in Figure 15.

Figure 15: Distribution of rare earth mineral occurrences (from Orris and Grauch, 2002).

[24] Princetown University news release 2006, *Two miles underground, strange bacteria are found thriving* (http://www.princeton.edu/main/news/archive/S16/13/72E53/index.xml?section=newsreleases).

12. Options for Enhancing the Private Sector's Contribution to Groundwater Governance – an Initial Assessment

The shallow crust of our planet, from near surface to depths of several kilometres (i.e. the maximum commercially reachable depths with present drilling technologies) contains resources that are essential for human development and well-being: water, energy, geologic materials (minerals and construction materials) and space. While this is apparent and widely recognized, efforts to improve our knowledge and understanding of the geological conditions and active geophysical and thermodynamic processes at depth have been generally conducted in a fragmented way, sector by sector, with little interchanges of knowledge and experience, thus hindering the achievement of the level of integrated reconstruction of the subsurface, which would be needed for introducing sustainable governance principles. Due to the high costs and technological sophistication of subsurface information gathering, this is particularly true for developing regions of the world, where countries often lack the capacity and knowledge necessary for the sustainable long-term management of their own underground resources.

Groundwater is no exception. What lies below the first unconfined aquifers is often scarcely known by those with administrative responsibilities in natural resources planning. Notwithstanding the fact that groundwater research and regional aquifer studies are critical elements of the future health of the economy and the environment, the current level of funding for regional groundwater resource work is inadequate to deal with future needs, even in the developed world.

Over the decades, the energy and mining industry has developed a unique wealth of organized information on the subsurface and has consequently acquired the ability to minimize the mining risks involved in searching for hydrocarbons, geothermal heat and mineral ores. Huge investments have been, and continue to be made, in order to improve the understanding of subsurface geological conditions in prospective regions globally, on land and beneath the ocean's floors. The results of these tremendous exploratory efforts have largely and understandably remained property of the investors and of service and consulting firms. Competition has prevented in most cases the broad circulation of this unique patrimony of expertise and knowledge. In some cases however, as a for example in the Saharan region and the Arabian Peninsula, oil exploration has led to the discovery of huge, albeit non-renewable, high-quality deep-seated groundwater resources, which are now being successfully exploited. Without the investments of the oil industry this would have never happened.

There are few if any industrial processes that do not need a constant supply of high-quality water, and some industrial sectors are major water users. For example, one of the most significant variables for the entire mining industry, in terms of current operations as well as the materialization of future projects, is the availability of water. Mineral processing requires water, whether it be flotation, leaching or any other kind of process. Water and energy issues are also interconnected; for example, the delivery of water depends on energy for pumping, and many forms of energy production require a dependable water supply. Other private stakeholders that in various ways interact with groundwater are the soft drinks and beer industries[25], obvious major water users, as well as bottled water producers, water utilities, the construction sector and the agro-industry.

All groundwater users – from the large private multi-national enterprises, to the farmers and the urban planners – recognize the need for improved knowledge on, and governance of, groundwater as key foundations of the sustainable long-term use of this precious resource. The challenge however exceeds the mission or capabilities of any one intergovernmental, governmental, university, public or private sector entity. As a consequence, each of these entities has a supporting role to play in protecting human health and the environment by contributing sound technical guidance on groundwater issues.

International organizations, governmental bodies, academia, geological surveys as well as professional and users associations are keen to join forces and spearhead this endeavour. However, the private energy and mining industries, the water companies, the service and consulting firms and other private stakeholders, until recently, have not had any platform to discuss groundwater governance in particular. But new initiatives are developing. For example, the World Business Council for Sustainable Development (WBCSD) provides an

[25] More than 90 percent of beer is water and an efficient brewery will typically use between 4 and 6 litres of water to produce one litre of beer.

opportunity to discuss water governance in general[26]. Beyond this, there are still huge challenges for making the private sector's wealth of information and knowledge on the underground available to all parties in the groundwater governance debate. In the case of groundwater and development of the underground space, without private sector commitment, expertise, knowledge, and financial resources, the governance of groundwater and the management of the subsurface might prove impossible or simply lead to more overly-bureaucratic regulation. This may inhibit innovation in the management of the underground space rather than encourage good practice. Opportunities for cooperation will have to be explored based on an assessment of the multiple, sector-specific benefits that the private sector may derive by investing its expertise and human and financial resources within the context of an international effort to promote groundwater governance and contribute to expand the knowledge of the groundwater resource.

[26] See WBSCD website for more information (http://www.wbcsd.org/work-program/sector-projects/water.aspx).

13. The Future Role of Hydrogeologists in Regulating the Underground Space

In 1999, the British Geological Survey in its official magazine *Earthwise* published the following statement:

> The last decade has seen the rapid development in the utilization of underground space and this development seems to be only the beginning of the race for space.

Encouraged by technological advances, the race is now on, particularly in urban areas and mega-cities, where demand for subsurface space is rapidly growing, and in response to our crowded world's ever increasing needs of storage space, groundwater resources and energy. As urbanization and infrastructure are more and more interacting with groundwater resources and underground geological materials, the need grows for geological expertise in the multi-purpose planning of subsurface use. In parallel, if geologists want to meet the new challenge, they will have to adapt to this new role, and acquire the broad and multidisciplinary vision necessary to become key advisors in defining and implementing policies for the sustainable utilization of subsurface space and resources. Hopeful opportunities do exist, especially if hydrogeologists follow this call to action to strive for progress in both the science issues as well as the societal/political debates involved.

The Deep City Project presented in 2006 by the University of Lausanne, Switzerland, shows an interesting approach to subsurface regulations (Figure 16). The project, motivated by the critical congestion of many cities around the world leading to environmental and public health problems, shows a full understanding of the potential role of geology: "Defining the rules for multi-uses of the resources must take into consideration the various geological formations present below the city and their properties. As underground conditions are very variable from a city to another and even variable at the scale of a city, geological knowledge and 3D modelling is the first step in the process of planning the long-term multi-uses of underground space." This planning must consider the resource of space for underground construction, but also other underground resources such as geomaterials, groundwater and geothermal resources. The management of the urban underground must not be sectorial but must integrate the potential of all these resources.

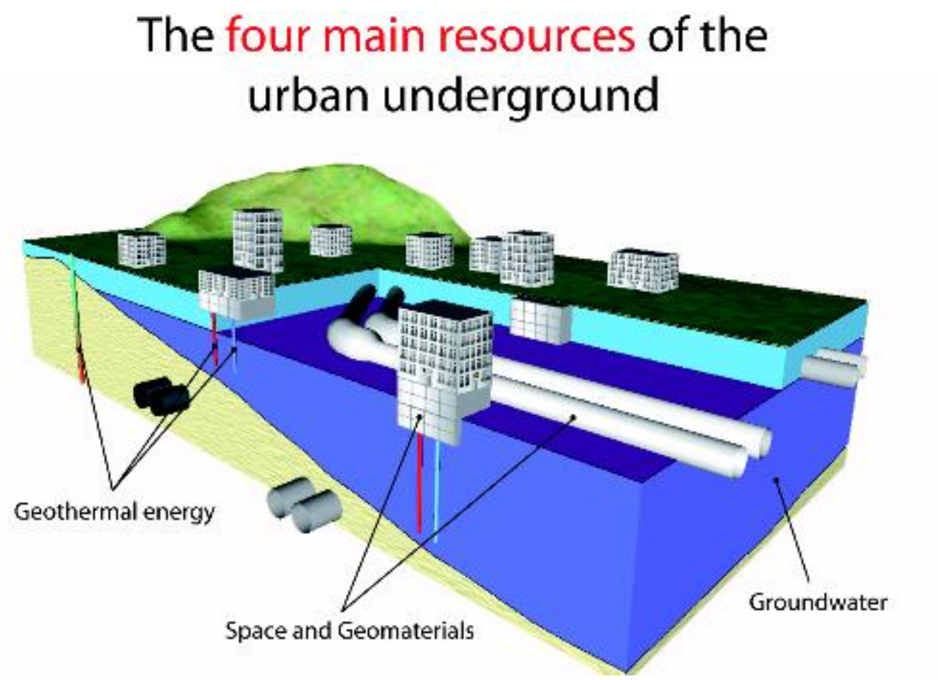


Figure 16: The four main resources of the urban underground. From "DEEP CITY project" (NRP 54) by Parriaux Aurèle, Tacher Laurent, Blunier Pascal, Maire Pierrick, 2006.

14. Conclusions

The subsurface and its resources are currently used for many purposes: abstracting groundwater; extracting minerals, oil and gas; developing geothermal energy; waste disposal; storage and recovery of substances and heat; and accommodating technical infrastructure. There is a general trend towards more intensive use of the subsurface and its resources.

Although these different categories of use are currently or potentially interfering, management and governance are fragmented over the individual categories of use. The degree of control to prevent environmental impacts and other externalities varies geographically and according to type of use from virtually absent to satisfactory. Deep aquifers so far are only sparsely tapped around the world for abstracting freshwater. They certainly offer opportunities for more intensive exploitation, in particular as an emergency resource and as a buffer for mitigating climate change impacts. Nevertheless, most deep-seated aquifers have no or only little recharge and thus offer mainly non-renewable resources. Depending on depth, deep-seated aquifers may come under different legislation and institutional mandates than aquifers at more shallow depth (mining *versus* water resources).

Mining and hydrocarbon activities traditionally follow an approach focused on detail rather than broad groundwater management. They pose considerable risks to groundwater resources and the environment and therefore need to be strictly regulated to prevent damage. Countries with weak legislation and enforcement capabilities are likely to be faced with a growing legacy of resource and environmental problems.

Although its use is annually growing at a rate of 14 percent, geothermal energy remains today an underdeveloped energy resource, compared to the vast amount of thermal energy offered within the Earth's crust. Access to a huge resource that will last thousands of years is theoretically possible, but requires a number of serious technical and financial constraints to be overcome.

The subsurface is progressively being used for storage of hazardous waste such as nuclear waste and other liquid or solid wastes. Related activities (often using similar techniques such as injection wells) are the injection of fluids for soluble mineral extraction, the storage and recovery of heat and hydrocarbons, carbon capture and sequestration (CCS), hydraulic fracturing ('fracking') and the injection of residual geothermal fluids. All these activities lead to pollution of the subsurface with exotic substances, many of which may be harmful or even dangerous.

Strict adherence to adequate regulations therefore are necessary to protect the subsurface environment and related resources. Such regulations exist and are imposed in some countries, while in other countries they are absent, insufficient or not enforced. Against some types of hazardous waste disposal strong public opposition is observed (action groups), especially related to nuclear waste disposal and to CCS, usually because the government is not transparent or there is no confidence in the government's risk assessment and/or the quality of the intended protecting measures.

Nuclear weapons testing is not intended as a method to bring substances into the subsurface, but it does result in nuclear contamination of the subsoil which is a sensitive issue. Therefore, strict protocols and careful investigations are needed to avoid serious degradation of the subsurface.

Use of the subsurface space for underground pipelines, cables, car parks, buildings and other technical infrastructure is increasing. Regulations on such underground construction activities probably do exist in most countries, but compliance may be weak in many cases. Moreover, the subject is rarely included in regular groundwater management plans. Problems that arise tend primarily to affect the underground constructions themselves rather than the externalities they produce.

Planning the different categories of activities related to the subsurface is in most countries extremely fragmented and uncoordinated. Tendencies towards integrated management of the use of the subsurface and its resources can be observed in some countries. Integrated management certainly has the potential to reduce problems and thus to bear fruit.

In the endeavours to establish adequate governance, several barriers and constraints are encountered. They include lack of data and information; insufficient institutional capacity and mandate; lack of funds; inadequate legislation and regulatory frameworks; and many deficiencies in the government's capability to understand/analyse the problems, develop a vision and adequate plans, communicate transparently, gain confidence of the population and implement the required measures.

Smarter regulation of the utilization of underground space and resources will secure social and environmental benefits. This may help reconcile the role of the private sector and public interest with the potential to reduce public-private conflicts of interests. However, worldwide there is still little vision on how to exploit non-renewable fresh groundwater resources for optimal societal benefit.

Promising elements to achieve improved governance of the subsurface and its resources in the near future are technological progress; a closer co-operation between the public and private sector; involvement of the civil society; and a stronger involvement of geologists and hydrogeologists in the debate on the subsurface and its resources, and in the development of strategies and plans for their management.

Therefore, while almost all deep groundwater developments and subsurface activities are expensive, they can be technically engineered to be safe and sustainable. However, a mix of demographic, political and development pressures have led to the implementation of projects without necessarily a full understanding of their probable long-term hydrogeological and environmental impacts. When environmental damage has occurred, this has often resulted in long-term disputes between the public, politicians and private enterprises over liabilities and responsibilities for remediation. While governments may respond in time to address the problems with appropriate legislation, the legacy of damage to aquifers tends to remain and incite public action.

Given that the default position of public and private enterprises is generally that of denial or shifting blame, in aquifer systems the identification of who has been responsible for particular pollution damage can impose a large burden of proof on the plaintiffs. In many cases, the public has developed an entrenched distrust of the big corporations and their development plans. While this position is being brought under strong governance in the wealthier nations, many other states with politicians driven by the wish for rapid growth and poverty reduction often feel compelled to accept internationally-funded developments that in the long term will prove to continue the legacy of environmental damage.

Finally, there is much need for coordinating or even integrating legislation and institutions aiming for the proper management and control of the different uses of the subsurface and its resources. Changing this current experience with project operators and developers who failed to exercise the proper control of their activities suggests that international policies are required to force them to do so by imposing selective trading and/or financial and legal penalties.

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Appendix 1

United States Environmental Protection Agency – 2012 Classification of Injection Wells (UIC Regulations)

In the USA injection wells first came into use in the 1930s to dispose of oil field brines. When the practice became common in the 1960s and 1970s, groundwater contamination problems were frequent due to well integrity failures. These were addressed by the US 1974 Safe Drinking Water Act and the 1980 US EPA Underground Injection Control (UIC) Regulations (US EPA, 2001). In the USA, each State has primacy over adapting and applying the Federal EPA guidelines and regulations providing that they meet the minimum US EPA requirements or that the State regulations achieve the same or a higher degree of protection of the Underground Source of Drinking Water (USDW[27]) aquifers.

The US EPA UIC Programme is designed to regulate the construction, operation, permitting and closure of injection wells that place fluids underground for storage or disposal. The 2012 US EPA classification for injection wells is shown in Table A5.1. Comprehensive US EPA reviews of each injection well class are available.

Table A5.1: Injection Well Classification based on US EPA 2012[28]

US Environment Protection Agency Classification	Injection Well Description	Number*
Class I	Wells used for disposal of industrial & municipal waste inject far below the lowermost USDW	4 841*
Class II	Wells used to inject fluids associated with oil and natural gas production	1 500 000*
Class III	Wells used to inject fluids for the extraction of minerals	19 9253*
Class IV	Wells used to dispose of hazardous or radioactive wastes into or above a USDW	540*
Class V	Wells are used to inject non-hazardous fluids underground	650 000
Class VI	Wells used for injection of carbon dioxide (CO_2) into underground subsurface rock formations for long-term storage, or geologic sequestration.	

* Number taken from the Ground Water Protection Council, 2007

The 2012 US EPA Class II includes three categories of wells used to inject fluids associated with oil and natural gas production wells (Abridged USA EPA Text): i) *Enhanced Recovery Wells* inject brine, water, steam, polymers or carbon dioxide into oil-bearing formations to recover residual oil and – in some limited applications – natural gas; ii) *Disposal Wells* inject brines and other fluids associated with the production of oil and natural gas or natural gas storage operations. Class II disposal wells can only be used to dispose of fluids associated with oil and gas production. The 2012 US EPA records show approximately 144 000 Class II operational wells injecting over 7.57 Mm^3 of oilfield brine per day. Disposal wells represent about 20 percent of Class II wells; iii) *Hydrocarbon Storage Wells* inject liquid hydrocarbons in underground formations (such as salt caverns)

Broadly the use of Class V non-hazardous fluid injection wells falls in to three categories: for the disposal of treated and untreated domestic, business, agricultural and industrial waste and surface water drainage into or above USDW aquifers; for returning water extracted for thermal heating and cooling or geothermal power generation; and for aquifer recharge, aquifer storage and recovery, aquifer remediation, creation of saline

[27] A USDW is defined as an aquifer or a portion of an aquifer that: 1. supplies any public water system; or 2. contains sufficient quantity of groundwater to supply a public water system; and i) currently supplies drinking water for human consumption; or ii) contains fewer than 10 000 milligrams per litre (mg/L) total dissolved solids (TDS). **NOTE**: Although aquifers with greater than 500 mg/L TDS are rarely used for drinking water supplies without treatment, the Agency believes that protecting waters with less than 10 000 mg/L TDS will ensure an adequate supply for present and future generations.

[28] See US EPA website (http://water.epa.gov/type/groundwater/uic/, updated of - Thursday, March 15, 2012).

intrusion barriers, subsidence control and for wells used to test new technologies. The US EPA[29] sets out the permitting requirements and applications for 22 Class V specific well applications. Aquifer recharge wells and ASR wells (storage and recovery) are included in Class V[30]. However, the EPA classification of wells appears to have been revised since the 1999-2001 reviews with some Class V wells for example used for In-Situ Fossil Fuel Recovery Wells now reassigned to Class III.

While current USA federal and state EPA regulations have severely restricted new USDW aquifer contamination, the effects of legacy waste disposal contamination and agricultural practices was widely detected in many public water supply wells in the late 1990s (US EPA, 1999b).

[29] http://water.epa.gov/type/groundwater/uic/class5/classv_study.cfm#two.

[30] Full EPA review at: http://water.epa.gov/type/groundwater/uic/class5/upload/2007_12_12_uic_class5_study_uic-class5_classvstudy_volume21-aquiferrecharge.pdf.

Thematic Paper 11

MANAGING THE INVISIBLE: THE GOVERNANCE AND POLITICAL ECONOMY OF GROUNDWATER

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Acronyms

AMCOW	African Minister's Council on Water
APDAI	Andhra Pradesh Drought Adaptation Initiative (India)
APFAMGS	Andhra Pradesh Farmer Management Groundwater Systems Project
AusAID	Australian Agency for International Development
Bank	World Bank
CAAC	Catchment Area Advisory Committee (Kenya)
CAS	Country Assistance Strategy
CGWA	Central Ground Water Authority (India)
CGWB	Central Ground Water Board (India)
CSEC	National Council for Water and Climate
CWRAS	Country Water Resource Assistance Strategy
DAWASA	Dar es Salaam Water and Sewerage Authority
DAWASCO	Dar es Salaam Water and Sewerage Company (Tanzania)
DFGG	Demand for Good Governance
DfID	Department for International Development (UK)
DoS	Department of Statistics (Jordan)
DWA	Department of Water Affairs (South Africa)
DWQ	Drinking Water Quality
EMPOWERS	Euro-Mediterranean Participatory Water Resources Scenarios
EPA	Entry-Point Activity
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GAC	Governance and Anti-Corruption
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEF IW	Global Environment Facility International Waters
GMMR	Great Man-Made River
GNI	Gross National Income
GRACE	Gravity Recovery and Climate Experiment
GRIP	Groundwater Resource Information Project (South Africa)
GW	Groundwater
GW-MATE	Groundwater Management Advisory Team
GWP	Global Water Partnership
IAEA	International Atomic Energy Agency
IAH	International Association of Hydrogeologists
IEG	Independent Evaluation Group
IGRAC	International Groundwater Resources Assessment Centre
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
kl	kilolitre

km^2	Squared kilometres
Ksh	Kenya Shilling
M&E	Monitoring & Evaluation
MENA	Middle East & North Africa (region)
mm	Millimetres
m^3/yr	Cubic metres per year
Mm^3/yr	Million cubic metres per year
MoWI	Ministry of Water Infrastructure (Jordan)
NABARD	National Bank for Agriculture and Rural Development (India)
NGO	Non-Government Organization
NSAS	Nubian Sandstone Aquifer
NWRS	National Water Resource Strategy (South Africa)
NWSSIP	National Water Strategy (Yemen)
OECD	Organization for Economic Co-operation & Development
PE	Political Economy
PES	Payment for Environmental Services
PROFODUA	Water Rights Formalization Programme (Peru)
R	South Africa Rand
SADC	Southern Africa Development Community
SANS	South African National Standards
TTL	Task Team Leader
TWIWA	Transport, Water, Information and Communication Technology Water Anchor
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific & Cultural Organization
UNESCO-IHP	United Nations Educational, Scientific & Cultural Organization – International Hydrological Program
URV	Unit Reference Value
US$	United States Dollar
WASREB	Water Services Regulatory Board (Kenya)
WBI	World Bank Institute
WQAA	Water Quality Assessment Authority (India)
WRMA	Water Resource Management Authority (Kenya)
WRSS	Water Resources Sector Strategy (World Bank)
WRUA	Water Resource Users Association (Kenya)
WTE	Water Trading Entity (South Africa)
WUA	Water User Association
WWQ	Waste Water Quality

Executive Summary

The Groundwater Challenge

Groundwater is playing an increasingly important role in domestic, industrial and agricultural water supply.

With the advent of the tubewell and driven by the rapid growth of demand for agricultural and municipal water, annual global groundwater extraction has rapidly increased in recent decades, from 100 km^3 a year in 1950 to the current use of about 800 km^3 a year (Wada *et al*., 2010; Margat, 2008). Today, 43 percent of global irrigation (Siebert *et al*., 2010) as well as more than 50 percent of the world's drinking water supply (Zekster & Everett, 2004) and a large share of global industrial activity depend on groundwater. In addition, its capacity to answer growing water demand, groundwater also provides unique opportunities to cope with increased climate variability due to climate change.

This ever increasing reliance on groundwater has gone largely unnoticed but has become a vital input to our economies.

In a large number of countries, groundwater is the foundation on which agriculture, urban development, rural jobs and safe drinking water supply systems have been built; groundwater has become a major contributor to GDP. Indeed, access to groundwater through private tubewells was a key factor in South Asia's Green Revolution. This explosion of groundwater use has occurred in a largely unplanned and uncontrolled way, taking place almost unnoticed in many countries because of its decentralized nature.

In many places the unplanned and massive use of groundwater has resulted in serious and growing problems of depletion and quality deterioration.

In many locations, over-abstraction has resulted in sharp declines in the groundwater table and at times even to exhaustion of the resource. In other areas groundwater resources are gradually rendered useless as a result of pollution. Major sources of groundwater pollution are infiltration of untreated waste water under cities, pesticides and nitrates from agricultural activities, and effluents from industrial and mining activities. Probably even more dramatic is the loss of groundwater resources to indirect pollution from geological sources that are the result of poor aquifer management. These include saline water intrusion in coastal aquifers and the gradual pollution of aquifers by toxic elements like arsenic, fluoride and radioactive isotopes

Need for Governance

New, more effective governance is essential to respond to the challenges outlined.

Governance—the operation of rules, instruments and organizations that can align stakeholder behaviour and actual outcomes with policy objectives—has to respond to these serious problems. Essentially, governance frameworks are ill-adapted to control the sharp increase in the private exploitation of groundwater.

As a result of its defining characteristics, groundwater governance is inherently more complicated than that for surface water.

Unlike surface water, <u>groundwater is easily appropriated simply by capturing it (the 'law of capture')</u>. Although like surface water it is a common pool resource, the fact that groundwater is not readily visible combines with well technology to allow individuals to establish *de facto* rights to the water under their land. Also unlike surface water, <u>there is no built-in need to cooperate within a governance framework</u>. The individual character of groundwater frees the user from constraining governance or cooperation with neighbours. Finally, it is <u>hard to measure this unseen resource</u>, and it is difficult to manage what you cannot measure. All attempts to impose governance over groundwater and to bring groundwater within an integrated water resources management (IWRM) framework have to take account of these three characteristics.

Governance today also has to take account of the reality that in many locations "the cat is out of the bag."

Once groundwater rights have been asserted ahead of a governance system that might have contained them, it is incredibly difficult to recover control. This is especially true in countries where all the incentives are in favour of development and abstraction, particularly where agricultural policy coincides with farmers' own motives to produce ever more. These external incentives are compounded by the powerful incentives inherent in the resource itself that lead farmers to prefer groundwater to all other water sources.

Despite the magnitude of the challenges and problems, groundwater governance has not been on the agenda of decision makers.

Groundwater has failed to feature prominently in water policy dialogue at the local, national or global level. As a result, its governance has not kept pace with increasing demands and technological advances. Analysis of the World Bank portfolio shows that despite the sound analytical studies and available expertise, there has been a decline in the number of groundwater projects financed. Moreover, of those financed few included a component on groundwater governance.

The aim of this report is, therefore, to help to put groundwater and its governance at the top of the agenda for decision makers and practitioners.

To that end, the report tries to answer the following questions:

- Why has groundwater governance failed to stop the emergence of very serious threats to the resource?
- What are the impediments to improving groundwater governance?
- What are the options to overcome those impediments?

Implicit in the report approach is recognition of the importance of groundwater resources in promoting developing country adaptation to predicted climate changes.

The analysis draws on country level experience in implementing global approaches to groundwater governance. This comprises in-depth case studies from five countries: India, Kenya, Morocco, South Africa, and Tanzania. Analysis of impediments to improving good governance and options to overcome them also includes best practice experiences obtained from an analysis of non-Bank international groundwater experiences.

Analytical Framework

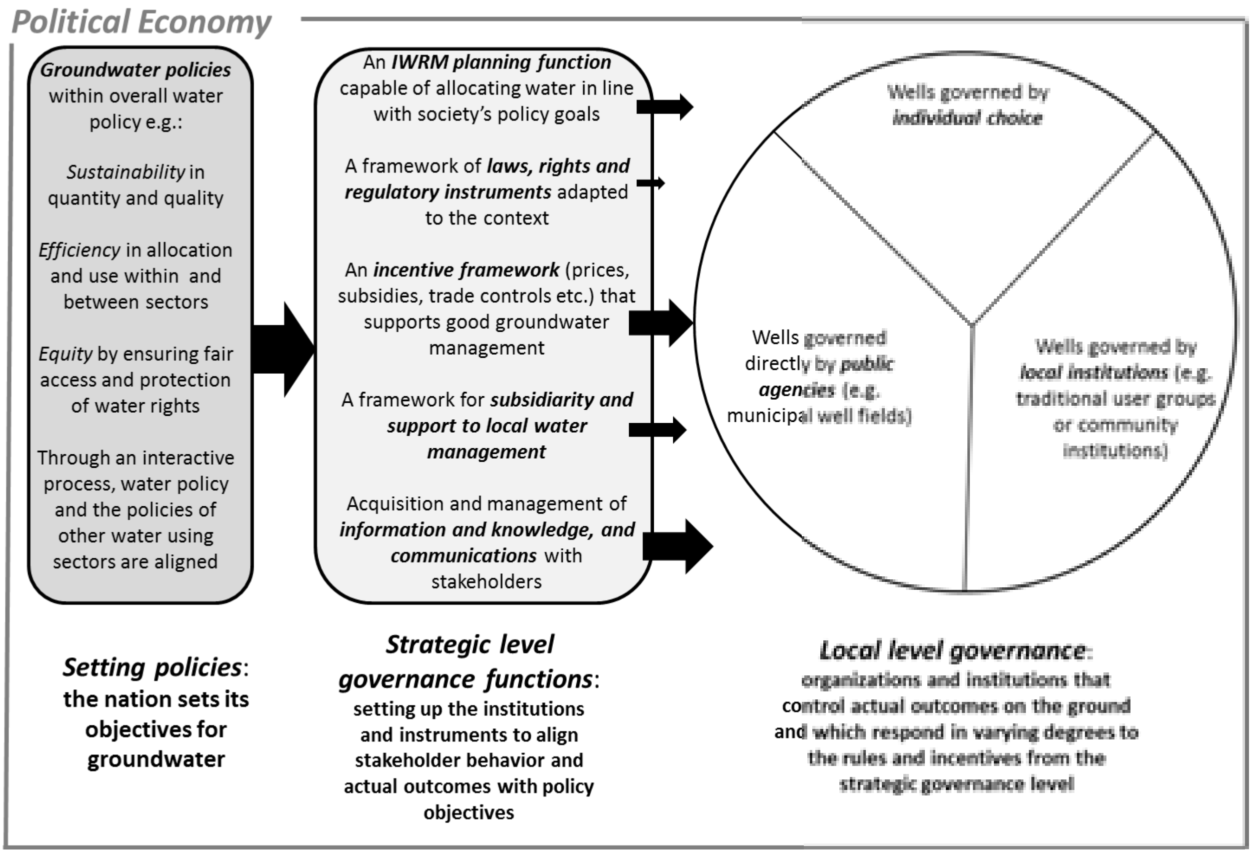
The framework used for the analysis distinguishes three parts to the groundwater governance system: the policy level, the strategic level and the local level governance. Nations establish their groundwater objectives at the policy level. Strategic level governance is the stage at which a nation puts in place institutions and instruments to align stakeholder behaviour and actual outcomes with policy objectives. Finally, local level governance involves the organizations and institutions that control actual outcomes on the ground, and respond in varying degrees to rules and incentives. The framework is sketched out in Chart 1.

Case Studies of National Governance Arrangements

In all countries studied, groundwater development and abstraction have taken place ahead of governance arrangements, leading to depletion and quality deterioration.

The case studies provided a rich variety of lessons, many of which were shared by several or all of the countries. All countries studied were suffering depletion and quality deterioration of the aquifers to a greater or lesser degree. All five countries had policy frameworks in place, but groundwater policies were generally poorly articulated with those of the water-using sectors, particularly agriculture. Formal governance arrangements were largely top down, although there were some cases of decentralization to the basin level as well as some moves towards creating partnerships with local collective management organizations. However, in every case the rights and regulation approach to governance was proving to be not well adapted to the fast changing realities of the "groundwater revolution," and everywhere implementation capacity fell far short of the ambitious regulatory provisions.

Chart 1 - A Framework for Analyzing and Assessing Groundwater Governance



Information, knowledge sharing and communications were insufficient to support management or to foster good governance.

Information on groundwater resources was generally weak, although adequate for management approaches to be determined. Information sharing was poor in all the countries reviewed, and systematic communications programs scarcely existed. Public agencies were also under-financed and lacked the capacity to do an adequate job.

At the local level, there was generally a big disconnect between the regulatory regime and facts on the ground, and in some cases local collective management was substituting for more formal governance.

For example, rules on drilling and abstraction, on pollution and on protection of recharge zones were not always applied on the ground. Some initiatives to delegate management to the basin level appeared more promising. At the local level, there were a number of interesting examples of collective management and self-regulation, but these were weakly embedded and little linked to public sector support structures.

Constraints and Options for Setting Good Groundwater Policy

<u>The Influence of Context</u>

Groundwater is particularly challenging for governance, because millions of well owners have appropriated it, and they respond more to powerful economic incentives than to the rules governance would impose.

Groundwater is a common resource, but driven by strong economic incentives people have established *de facto* individual rights to groundwater. Moreover, they are competing with each other to extract as much as possible as quickly as possible with no inherent incentives to aim for sustainability. Governance is further challenged by the fact that groundwater, while it is part of the hydrological cycle, is largely unseen and even specialists are hard pressed to describe the resource and its interactions in sufficient detail to plan for and manage it.

Governance has to be adapted to the context and to capacity, and be tailored to the size and nature of the problem as well as to the objective targeted.

The challenge is increased by the local specificity of groundwater given that each area has its own physical, geographical and socioeconomic characteristics. Governance also has to adapt to the state of development and to the problems that past assertion of rights and abstraction behaviour have produced. In some cases the problem is over-abstraction and depletion, in others water needed by fast growing towns is "locked in" to lower yielding agricultural uses, and in yet other cases the challenge may be compromised quality or recharge. Usually, these problems do not occur in isolation, but more than one of them will exist at the same time. All these features need to be taken into account in assessing governance options, which have to be adapted to the context and to capacity, and be appropriate to the problem at hand and the policy objectives targeted.

<u>Setting Good Policy and Handling Political Economy Factors</u>

Policy makers have little incentive to strengthen groundwater governance.

Although most national policies target sustainability, equity and efficiency, there is a gap between stated policy and what actually happens. Policy makers have short horizons and inadequate information, and they are reluctant to put forward policies that constrain the profitability of groundwater use because this affects powerful constituencies and often the poor, as well. Policy makers prefer high-profile surface water investments to the long and politically costly struggle to impose order on a largely ungoverned groundwater sector.

Champions of change need to choose their causes carefully, identifying the really critical issues, and preparing and presenting the options persuasively.

These options should, as far as possible, reconcile the incentives of decision makers and stakeholders with some approximation of good groundwater policy. A first step is usually to get the budget and the go-ahead for essential resource assessments and for establishing a reliable monitoring and reporting system.

Governance at the Strategic Level

<u>IWRM and Cross-Sectoral Harmonization</u>

Groundwater is the "poor relation" in water resources management and is often over-ridden by economic interests, particularly agriculture.

Although most countries have adopted policies and have set up organizations for integrated water resource management (IWRM), groundwater struggles for its place in integrated water planning. Governments often fail to provide the capacity and budgets needed for implementing the groundwater parts of these plans. Improving groundwater governance requires stronger groundwater agencies.

The case needs to be made for the integration of groundwater into planning, for policy harmonization and (if possible) for "multi-level governance."

Governments need to align instruments and harmonize sector policies, planning and implementation at all levels, not only at the centre. Some good examples of this multi-level governance for groundwater are emerging.

<u>Developing and Applying Governance Approaches</u>

The analytical framework above distinguished three governance approaches, some or all of which are found in most countries:

- A <u>rights and regulation approach</u> awards (or recognizes) legal water rights to users and then ensures that users are respecting the terms of the award through a regulatory system.
- An <u>incentives-based approach</u> uses positive and negative incentives that typically affect the profitability of water use to align pumping behaviour at the wellhead with policy.

- A subsidiarity approach delegates responsibility for groundwater management to the local level, usually to stakeholder interest groups.

Rights and regulatory approaches are very demanding to implement and are usually resisted by stakeholders.

Rights and regulatory approaches are the most precise instruments for matching behaviour at the wellhead to society's goals, but are usually impeded by massive institutional and operational problems. Rights and regulation approaches have run into problems of defining, issuing and regulating quantified rights. Where these systems have been applied, they have run into significant problems of organizational capacity and have usually received scant compliance from well owners. Also, like many systems that essentially recognize past appropriations of the commons, they tend to confirm inequitable patterns of resource ownership.

However, for bigger and formal sector users, rights and regulation approaches are more feasible and can be the best approach.

Designing and implementing such systems can be done in some circumstances, but it requires a realistic feasibility assessment, especially of the cost and benefits compared to those from an incentives or subsidiarity approach. Combinations of approaches may be possible, for example registering just the bigger, more formal users (who can also be obliged to pay for the privilege), while adopting a subsidiarity approach for smaller users. However, care will always be needed to protect the rights of the smaller users.

Adjusting the incentives structure is a mechanism that even a weak government can undertake, but adjustments are politically difficult and can have negative or unintended consequences.

Positive and negative incentives are very powerful determinants of behaviour and, in the case of groundwater, governments are usually able to adjust them easily. Thus, they are attractive mechanisms, especially in a poor country with limited administrative capacity. Options include adjusting input prices like energy or output prices like farm produce; providing subsidies to encourage specific behaviours; or imposing bans on crops or on irrigation methods, for example. However, all these approaches have also big disadvantages. Adjusting prices often produces unintended consequences and can be politically damaging. Subsidies are expensive and lend themselves to corruption. Bans often run counter to economic efficiency.

Delegating to local governance structures can produce good results, and a framework for encouraging subsidiarity should be in place.

In principle, subsidiarity (that is, delegating management to the lowest possible level) is attractive because it comes closest to the actual decision makers, the millions of individuals drilling and operating wells. In some cases, collective management approaches at the local level have demonstrated good outcomes, often in partnership between stakeholders and local public agencies or projects. In most countries, the enabling framework should certainly encourage such approaches.

A mix of approaches will normally be indicated. This requires flexibility, adaptation, and keeping an eye on equity.
Overall, there is no one right approach. In each context, one or more of the three approaches may be better. Flexibility, piloting initiatives, and learning and adapting as needed are likely to be good stances. Particularly important is to adapt approaches to implementation capacity. In all approaches, it is essential to keep an eye on equity considerations, as there are powerful incentives pushing towards resource capture by the more powerful.

Table 1. Governance Approaches to Groundwater (including the requirements of each and when they might be the most indicated)

Requirements	Which approach may be the most effective?		
	Rights and regulation	Incentive structure	Subsidiarity
Is there a legal framework of rights and regulatory instruments that is adapted to the situation and which is implementable? If yes…	✓		
Is there a pattern of groundwater users complying with authority? If yes…	✓		
Is the approach administratively simple and low cost?	✓	✓	✓
Is there strong social capital and/or a history of agreed water rights and collective management at the local level? If yes…		✓	✓
Is inter-sectoral water transfer an objective? If yes…	✓	✓	
Is there a serious depletion problem? If yes…			✓
Is there a serious pollution or recharge problem? If yes…	✓		✓

Information, Knowledge and communications

Information, knowledge and communications functions are essential components of good groundwater governance.

Information on groundwater is very weak in most countries. This is due to high costs of collection, to prevalent capacity and skill gaps, and to lack of commitment and resources. Information is needed not only on aquifer characteristics but on uses and users, in order to understand behaviour and trajectories. Once collected, information has to be available to managers and to all stakeholders through an open information policy.

It is thus vital to persuade governments to invest in information and knowledge.

Economic assessments showing the value of groundwater and the cost of inaction may help persuade decision makers to invest in groundwater information and knowledge. Innovative ways of gathering part of the information through stakeholder participation or by using remote sensing technologies may lower costs. Increased attention is needed to getting to know uses and users, and to understanding motives and incentives local people face.

Communications with stakeholders is the key to developing governance systems with which stakeholders feel invested.

Very importantly, transparency, dialogue and interactive communications and learning are key to strengthening stakeholder ownership of governance, and to improving compliance and thereby outcomes.

Conflict and Conflict Resolution

Hitherto rare, conflict over groundwater is becoming more frequent.

Because groundwater extracted by tubewell was a new and abundant resource, the early stages of the groundwater revolution saw little conflict. In addition, because of the nature of groundwater, conflict has typically been much less than in the case of surface water. However, there are many potential sources of conflict now emerging due to over-abstraction, pollution, or changes in land use. Owners are often also in conflict with public agencies (for example, over regulation).

Furthermore, climate change is introducing costs and risks that are hard to manage, including increased demand for groundwater and reduced recharge, with consequent heightened risk of conflict. Disputes have also started to emerge between states over transboundary aquifers.

Although new dispute resolution mechanisms are being set up and old ones are being adapted, results vary.

Results are mixed regarding dispute resolution mechanisms. Traditional ones are difficult to adapt to the tubewell. Nevertheless, some are showing "adaptive capacity" and modern dispute resolution mechanisms are also being set up, sometimes alongside the old. Overall, dispute resolution mechanisms may be modern or traditional, centralized or local, but the key criterion is that they be accepted as fair by all parties.

The Role of Participation and Local Collective Management in Good Groundwater Governance

Empirical evidence suggests that participation and local collective management can be effective approaches to good water governance.

Participation appears to be effective in improving outcomes because it increases stakeholder ownership and because stakeholders often have access to information and can devise solutions better than or complementary to those delivered from the top down. Perhaps the most important aspect of participation is that it can align government objectives with those of local people. This gives the local stakeholders incentives to manage the groundwater well, and can empower them by giving them influence over outcomes during the implementation process.

Participatory approaches to groundwater management range from consultation to fully delegated groundwater management.

The more 'bottom up' the approach, the stronger the participation and empowerment of local stakeholders. Clearly the level of participation will depend on the local context, with the need for skilled support increasing as participation moves towards local collective self-management. In all this, it is salutary to recall that, in practice, local stakeholders are already managing most of the world's groundwater. In this sense, participation could be seen as much as participation by government agencies in local governance arrangements as vice versa.

Despite this potential there are many impediments to participation and local collective management.

Frequently, the legal and institutional provisions do not empower collective management institutions. For example, water user associations may be consulted over basin plans, but they rarely have any power to participate in decisions. At the local level, there is usually much more experience in collective management of surface water, and stakeholders are often very slow to adapt to the quite different demands of groundwater.

There is a risk that participatory approaches may reflect existing inequalities.

The more powerful may either dominate participatory deliberations or not participate at all. A further aspect of this asymmetry of power is that most people do not 'own' any groundwater, but they are nevertheless stakeholders. Ways to include and empower these people are often hard to negotiate, especially when there are social or cultural barriers. An equally challenging inclusion issue is how to get the participation of those who are not directly benefitting from the resource but who may be polluting or hampering recharge.

As groundwater problems intensify, incentives to participation and collective management grow.

User participation is complicated by the physical invisibility of groundwater systems, which make it harder to agree on the problems and on the responses and make monitoring more difficult. In fact, unless people agree there is a problem, stakeholders may not see the point of cooperating. However, crisis and the threat of climate change may change attitudes. Overall, a combination of social and physical conditions is likely to determine whether people cooperate. For example, settings where stakeholders are fewer and where resource dynamics are easier to understand are more conducive to cooperation.

Partnerships between local stakeholders and public agencies are an effective approach, but this requires long-term commitment on both sides.

Most successful collective groundwater management has not been done by local people alone, but in partnership with a public agency, which can provide knowledge, capacity building, and so forth. However, engaging in participatory approaches is costly and requires long-term commitment from public services and communities.

Experience yields some do's and don'ts: build on existing social capital, promote equity and inclusion, start in areas of good potential, go step-by-step, and learn lessons and adapt.

It seems that costs are less and outcomes better where participatory approaches build on existing social capital, and so interventions should be adapted to take advantage of it. Principles of equity and social fairness demand that the voices of the less powerful should also be heard, and this is something that public agencies can advocate. Interventions could start in areas with potential for success and where intervention costs are lower, in the expectation of spontaneous replication.

There is a wide range of methods and tools available to support stakeholder participation.

Experience around the world has yielded a number of approaches and tools that can be adapted and replicated. A suite of interactive learning processes has been developed that provides a range of flexible learning-by-doing approaches to developing institutions for collective water management. As part of this study, a simple readiness checklist was prepared to test whether the conditions for effective collective management of groundwater are in place. Finally, in general it is not a question of either/or, both top-down rules and public services as well as bottom-up local collective management are needed for effective groundwater management.

Getting Started Towards Improved Groundwater Governance

This report contains a perhaps bewildering set of issues and recommended actions. But every journey starts with the first steps. The following is a list of entry point activities on how to initiate help to countries to improve groundwater governance. Of course, not all these activities are applicable everywhere, but are offered as a menu of options:

- **Engage with the policy makers** to understand their concerns and constraints. Go outside the water ministry to seek harmonization and support from agriculture, planning, finance, and municipal development agencies. Carry out an economic analysis of key issues and present it persuasively. Recruit champions and try to come up with win-win agendas. Link governance reform to investment, if relevant.

- **Agree with policy makers on investment in groundwater knowledge**, and offer technical and financial support if needed. Focus not only on resources but on uses and users, identify hot spots. Draw on the results to persuade policy makers of the need for action. Link the results to an analysis of governance needs.

- **Help government to chart a reform path towards better groundwater governance**. Assess the needs and constraints to good governance, following the methodologies in this report. Identify what approaches are best indicated (rules and regulation, incentives, subsidiarity) and work out a reform path over time, as well as an actions and investment plan.

- **Help build strong groundwater organizations/departments/agencies** to ensure groundwater's place in IWRM planning and to strengthen their support to the governance approaches chosen. Match their capacity to the tasks decided upon. Dialogue with government to ensure that the organizations have adequately resources, including skills and budgets.

- **Identify the scope for collective management, and devise ways to support it.** Work at the project and local level, in tandem with agriculture colleagues and those involved in decentralization or local level government.

1. Background and Introduction

1.1 Groundwater as a Resource

Current Importance

Excluding water locked up in ice-caps and glaciers, groundwater constitutes 97 percent of the world's readily available freshwater. While historically it has not generally been exploited as heavily as surface water, recent large-scale development has meant that today it forms the foundation for social and economic development in many regions, particularly developing countries which account for 71 percent of global water withdrawals. It is estimated that groundwater is used for 43 percent of global irrigation water use (Siebert *et al*., 2010), 40 percent of total industrial withdrawals, and 50 percent of total municipal water withdrawals (Zekster and Everett, 2004) while also sustaining important ecosystem functions.[1] Beyond its sectoral importance, groundwater is often the sole water source in arid and semi-arid areas. It has been fundamental to rapid urban and rural development in Africa, Asia and Latin America. More than 1.5 billion urban dwellers depend on groundwater (Salman, 1999). Although spatial and sectoral reliance on groundwater varies greatly, it meets over 75 percent of national water needs in some countries.[2]

Furthermore, groundwater is predicted to play an increasingly critical role in addressing future global water needs. Developing country demand is expected to increase by more than 25 percent by 2025 (from 2010). Besides its capacity to answer growing water demand, groundwater also provides unique opportunities to cope with increased climate variability. Given its ever rising importance in answering global water demand and its potential for climate change adaptation it may seem odd that groundwater protection and management receive so little attention from the development community and remain low on the policy agenda. This paradox can be explained by the nature of groundwater and its unique characteristics.

Inherent Challenges

Groundwater differs from surface water in a number of characteristics (see Annex 1), which have implications for the development of appropriate governance structures.

The most striking feature of groundwater is its general invisibility, both physically and politically. The rapid and widespread increase in groundwater use has been termed by some hydro-geologists as a "silent revolution" due to its occurrence largely in an unplanned and uncontrolled way and almost without notice in many developing nations (Llamas and Martinez-Santos, 2005). In addition, the dynamics of many groundwater systems are not well understood. Furthermore, the ability to use groundwater "on credit" is a major advantage when facing increasing climate variability; however, it also poses a significant hazard to the sustainability of the resource if not governed effectively. A balance between meeting short-term needs and long-term utilization (and ecosystem demands) must be established.

Concurrently, and related to the physical challenges, groundwater is typically under-valued by governments (both in developed and developing countries), meaning that it is often weakly governed and underfunded and under-represented in water policy discourse.

Major Threats to Groundwater Systems

The quantity and quality of groundwater resources globally is threatened by unsustainable water withdrawals and consumption. This demand for groundwater is the result of rapid population and economic growth, increasing urbanization and commercial agriculture, and it is largely untrestrained by workable governance systems. Threats can be categorized into three major issues: (i) over-abstraction; (ii) encroachment over or degradation of recharge areas; (iii) and deterioration in groundwater quality. The first two can lead to depletion of the groundwater resource, and the second and third can affect its quality to the point where it may be unusable. The nature of groundwater as a common pool resource exposes it to Hardin's "tragedy of the commons," where inadequate management may lead inexorably to its degradation.

[1] There are uncertainties with the estimates. For example, Siebert *et al*. (2010) consider different approaches to estimating groundwater use for irrigation (the largest component of total groundwater use) and opt for a compilation based on national statistics and expert judgement as being the most reliable, albeit with considerable uncertainty.

[2] Including Estonia, Iceland, the Russian Federation, Jamaica, Saudi Arabia, Georgia, Swaziland, Mongolia, Libya, and Lithuania (International Groundwater Resources Assessment Centre (IGRAC))

Over-abstraction of groundwater commonly occurs due to the general practice of landowners asserting their rights to develop and abstract the water beneath their land. There have usually been no governance constraints on these *de facto* rights. As the well owner becomes aware that in fact the resource is shared, incentives are created to develop and pump out as much water as possible as quickly as possible. In many countries, the incentives are strengthened by price signals, particularly cheap diesel or electricity prices. In some areas, this combination of perverse incentives has led to the rapid depletion of reserves. In addition to using up often irreplaceable reserves, this can lead to rising costs and to rapid quality deterioration well before quantity is used up, as well as to secondary environmental effects and land subsidence (Foster *et al*., 2000).

Degradation of groundwater recharge areas, often through development activities and/or changes to hydrological regimes, can impact both the quantity and quality of recharge infiltrating into aquifers. A major challenge is determining the location and boundary of recharge areas and then controlling land uses there.
Deterioration of groundwater quality can come about through contamination from either point or diffuse sources. Aquifer vulnerability is highly dependent on physical characteristics (i.e. unconfined or confined) and local geology. While some contamination can occur naturally (for example, from naturally high levels of arsenic, fluoride and iron), anthropogenic sources generally pose a much greater threat. Pollution can render aquifers unusable if not controlled and remediation is often very difficult and expensive. Thus, the management focus should be on early, preventive actions combined with monitoring.

In addition to the three major threats identified above, climate change will likely have a profound impact on all stages of the hydrological cycle (precipitation, evaporation, runoff, river flows, groundwater recharge and discharge) affecting water availability and use across transboundary, basin, and local levels.

Groundwater reserves provide a first rate buffer against climate variability and any associated decline in other water sources, and will play an increasing role where aridity is on the increase. In addition, groundwater typically delayed response to climatic variability and its protection from evaporation means that it provides a water source that is itself naturally protected from increased variability under climate change. However, any compromised quantity and quality of groundwater resources may erode its advantages. In addition to investment in water-related infrastructure, strengthening of institutions that govern water use will also be required (World Bank, 2010a).

Need for Governance

Governance is understood as the operation of rules, instruments and organizations that can align stakeholder behaviour and actual outcomes with policy objectives (Chapter 2). This governance has to respond to the serious problems outline above. Essentially, there has been a surge in the uncontrolled private exploitation of the resource, and governance frameworks have been ill-adapted to control it. The result has been depletion and quality deterioration, and in some cases the misallocation of the resource to uses on which society places lower value.

Groundwater governance is inherently more complicated than surface water governance because of three defining characteristics. First, unlike surface water, groundwater is easily appropriated. Although groundwater, like surface water, is a common pool resource, well technology combined with the fact that it is invisible, allow individuals to establish *de facto* rights to the water under their land. Second, unlike surface water, there is no built-in need to cooperate within a governance framework. The individual character of groundwater frees the user from constraining governance or cooperation with neighbours. Third, it is very hard even for specialists to measure this unseen resource, and it is difficult (although not impossible) to manage what you cannot measure.

All attempts to impose governance over groundwater — and indeed to bring groundwater within an integrated water resources management (IWRM) framework — have to take account of these three characteristics. Governance today also has to take account of the reality that in many locations “the cat is out of the bag.” Once groundwater rights have been asserted ahead of any governance systems that might have contained them, it is incredibly difficult to recover control. This is especially true in countries where all the incentives are in favour of development and abstraction, particularly where agricultural policy coincides with farmers’ own motives to produce ever more. These external incentives are compounded by the powerful incentives inherent in the resource itself that lead farmers to prefer groundwater to all other water sources.[3] Governance frameworks have proved very frail in the past to resist such powerful motives, and traditional and local governance developed to manage springs or oases have rarely been able to adapt to the new tubewell technology. Very few governments have been able to align agricultural policy with good water resources management, and even fewer have been able to recover control over groundwater once that control has been lost.

Despite the magnitude of the challenges and problems, groundwater governance has not been much on the agenda of decision makers. Despite its importance to the livelihoods of a large proportion of the world's population, it has not been subject to adequate policy and management attention, particularly compared to surface water. Groundwater has failed to feature prominently in water policy dialogue at local, national or global level and as a result its governance has not kept pace with increasing demands and technological advances. However, select experiences from GW-MATE's case profiles demonstrated that integrated solutions for groundwater management and governance can lead to successful results.

Governance frameworks (Chapter 2) can provide a structure within which implementation of operational decisions (management) can occur, benefiting groundwater users (including the poor) and serving as a platform for the implementation of longer-term integrated water resources management (IWRM) principles. IWRM approaches include sharing of groundwater resources among competing users (including the environment) equitably and transparently, and in conjunction with surface waters.

It is a basic tenet of this report that improved governance arrangements are central to managing the "silent revolution." The need to promote awareness and action on groundwater governance to clients, coupled with increasing demands from the clients themselves, means that effective groundwater governance measures should be a high priority water sector issue for the Bank. This report contributes to those goals.

1.2 World Bank Groundwater Portfolio

The World Bank incorporates groundwater into its lending and analytical work including projects in Water Supply and Sanitation, Irrigation and Drainage, Energy,[4] and analytical assistance. The portfolio of Bank-supported groundwater work is reviewed briefly below.

Lending Projects

Decline in the Proportion of Groundwater Projects - Despite a substantial increase in investment in water portfolio projects since 2003, there has been a decline in the number and value of Bank groundwater projects. This decline is counter to the intention expressed in the 2003 Water Resources Sector Strategy (WRSS), where groundwater was identified as a sector priority.

Potential reasons for the low share of groundwater in water sector lending include: a general lack of appreciation by borrowing countries of both the potential of groundwater and the need to invest in its management; a reluctance of governments to borrow funds for groundwater investments compared to more prestigious and visible surface water infrastructure projects; and internal incentives at the Bank (to lend) that could be favouring investments in larger surface water infrastructure.

The most important reason, however, is probably the nature of public investment in groundwater. Most groundwater development is a private sector activity, and public intervention is mostly in governance, knowledge, management, capacity building, and institutional development. These are soft but extremely difficult and burdensome investments that are not inherently very attractive to governments.

Even if governments and the Bank were to increase this type of investment (see below), it would remain a small share of total investment lending. WRSS forecasts estimate that funding for water sector projects will increase to between $21 and $25 billion over FY10-13 (World Bank, 2010a). Groundwater software investment would need only a small share of this total, but those investments could require the Bank's knowledge and expertise

[3] Groundwater is usually cheap, of excellent quality, can be turned on and off like a tap, has natural storage, is ideal for supplementary irrigation, and so on.

[4] The Bank has provided funding for investigations and development of geothermal energy sources.

even more than for surface water. It will be essential to ensure that there are incentives for the Bank and for governments to identify and invest in groundwater governance projects.

From Groundwater Development to Groundwater Conservation — Bank groundwater-specific projects have shifted in focus from development in the 1990s to mitigation, conservation, and enhancement more recently (World Bank, 2010a; World Bank, 2009a) (Figure 1).

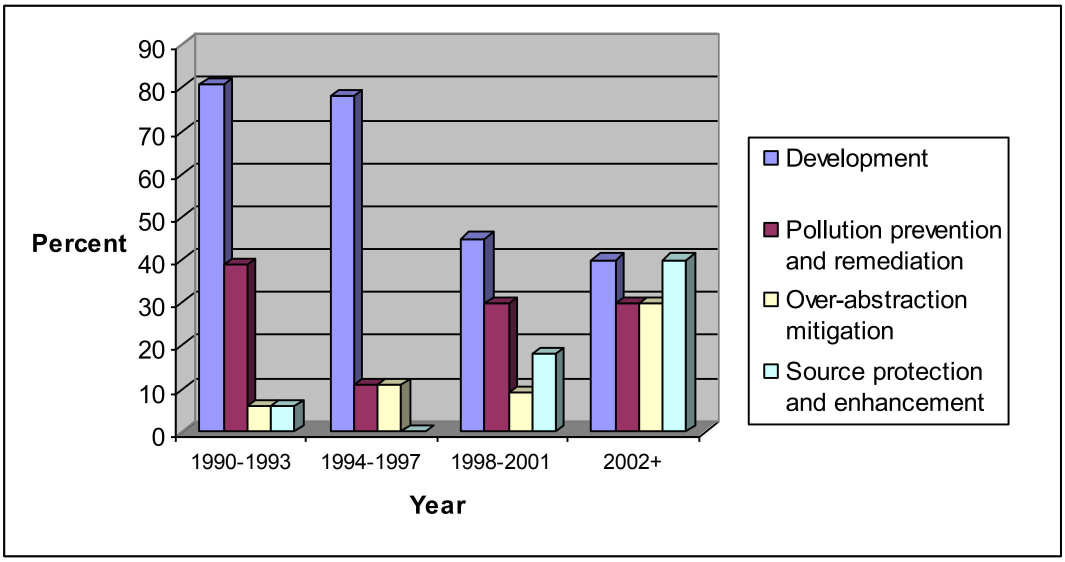


Figure 1. Primary Issues Addressed by the Focused Groundwater Projects

Note:Columns add to more than 100% because some projects addressed more than one primary issue.

However, technical rather than policy means have been predominant and very little attention has been given to establishing management frameworks to protect groundwater resources before development pressures arise. Only two of 46 reviewed groundwater-focused projects (both GEF-funded) were concerned with protecting a resource in advance of its exploitation.

Support to Governance Activities — Project emphasis on groundwater governance activities across the Bank portfolio is limited but increasing. Central governance components, such as institutional reform, devolution of management responsibility, and inter-sectoral coordination, did not form major components of projects with groundwater components during the 1997-2007 period. However, groundwater-specific projects did focus more on governance components, with over a quarter helping to transfer responsibilities from central institutions to local level.

Two GEF-funded transboundary groundwater projects active between 1997 and 2007 were focused on improving governance and developing analyses of issues and strategic action programs among the relevant countries. They also included in-country projects that provided assistance in instituting formal water rights and developing models for calculating safe yields.

Improved knowledge of the resource was the most common governance component, with less focus on clarification of entitlements to access. Policy and legislation can provide support for management of abstraction volumes and controlling polluting activities. However, policy or legislative reforms were scant. None of the 47 groundwater-focused projects supported water resource policy change and only four included legislative changes. Additionally, little emphasis was placed on raising public awareness or on financial reforms, and scant information about the specific features of groundwater and its management was evident (despite the need to overcome common misunderstandings about groundwater). While over a quarter of the projects with a focus on groundwater contained components that increased water user charges, the introduction of charging systems that more holistically reflect true resource costs and values were not pursued. However, some projects successfully promoted innovative approaches combining improved management and governance of groundwater and recognized the need to control water consumption rather than water use or withdrawal. Some integrated approaches to planning and management, including institutional cooperation and development at national, river basin, and provincial levels to promote a balanced top-down (from national and river basin levels) and bottom-up (participation from water user levels) management approach were evident.

Analytical Work

Country Water Resources Assistance Strategies - Country Water Resource Assistance Strategies (CWRAS) have been successful as a strategic tool for leveraging Bank engagement and dialogue on water issues (World Bank, 2010a). They provide a forum for discussing the major water resources issues facing a country or region and propose ways in which the World Bank can integrate water resources into its Country Assistance Strategies (CAS). While not providing in-depth details of groundwater issues, the CWRAS provide insights into the major groundwater issues in the respective country and region and may be useful for prompting policy dialogue.
A review of CWRAS reveals that the most frequently identified groundwater issue[5] is overuse, followed by contamination in specific regions (such as Eastern Europe, Asian and African cities). Degradation of recharge areas was considered a less serious issue where identified.

Country Water Resource Assistance Strategies are becoming increasingly prominent for governance in cases where resources had been over-abstracted. However, none of the CWRAS that proposed increased exploitation of groundwater included any governance activities to help manage the increased pressure on the resource.

GW-MATE and Knowledge Products - During the late 1990s and early 2000s, the Bank produced a number of technical publications on groundwater. In 2001, in partnership with DFID and support from the Dutch Government, it formed the Ground Water Management Advisory Team (GW-MATE) to provide expert technical support for the Bank’s work.

In addition to the Bank’s knowledge products on urban and rural groundwater management, legal and policy aspects, and groundwater quality management, GW-MATE produced an internationally recognized series of reports[6] and case study illustrations on key aspects of groundwater governance. GW-MATE also provided significant technical assistance to Bank staff and country managers.

One GW-MATE strategic overview paper[7] dealt specifically with groundwater governance, and provided a checklist of twenty technical, legal and institutional, policy coordination, and operational criteria for evaluating groundwater governance provision and capacity (which was used in Chapter 3 of this report for case study analyses). Other GW-MATE briefing notes dealt with aspects of groundwater governance including different legal approaches (Briefing Note 4), abstraction rights (Briefing Note 5), stakeholder participation (Briefing Note 6), and economic instruments (Briefing Note 7).

Portfolio Synopsis

In conclusion, despite the Bank’s sound analytical studies and available expertise, there has been a decline in the number of World-Bank-financed projects on groundwater, few of which have had a component on groundwater governance. Furthermore, the lack of willingness from governments to support this sector is partly explained by a limited appreciation of both the potential of groundwater and the importance of its governance and management. However, select experiences from GW-MATE’s case profiles demonstrated that integrated solutions for groundwater management and governance can lead to successful results. The main lesson is that helping countries to manage their groundwater resources better requires an intensive focus on the governance arrangements needed to achieve sustainability, efficiency and equity. Hence the value added of this report is to synthesize global best practice options that can then form part of government/Bank dialogue and investment.

1.3 Report Objectives, Methodology and Communications

Objectives

This report forms part of the GEF-funded Project on “Groundwater Governance: A Global Framework for Country Action” under the International Waters focal area, and includes partners from the FAO, GEF IW, IAH, UNESCO-IHP and the Bank. The project includes a broad review of issues, challenges and lessons drawing from national

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[5] In ten of nineteen CWRASs

[6] 16 GW-MATE Briefing Notes

[7] Strategic Overview Paper 1

and transboundary case studies. This report is one of twelve thematic papers and has a specific focus on the political economy of groundwater governance.

The aim of this study is to analyse the impediments to better governance of groundwater within a given political economy and propose recommendations to address key governance issues. Put simply, the report tries to answer the questions:

- Why has groundwater governance failed to stop the emergence of very serious threats to the resource?
- What are the impediments to improving groundwater governance?

- What are the options to overcome those impediments?

Implicit in the report approach is recognition of the importance of groundwater resources in promoting developing country adaptation to predicted climate changes.

Overarching objectives also include addressing the general "invisibility" problem related to groundwater, as well as strengthening the ability of Bank teams to undertake political economy and governance analyses related to groundwater (and thereby enhance the effectiveness of Bank operations in the water sector).

Methodology

The methodological approach of this study utilizes three lines of analysis to achieve its objectives.
First, the Bank's existing knowledge base of major groundwater management issues is synthesized in this chapter to draw lessons about support for groundwater governance. These lessons are taken from experience gained through GW-MATE-supported work, the IEG review of the World Bank water-related activities, the Water Anchor's portfolio review, as well as a review of CWRAS and other internal Bank documentation.
Secondly, the analysis draws on country level experience in implementing global approaches to groundwater governance. This comprises in-depth case studies from five countries: India, Kenya, Morocco, South Africa, and Tanzania (Table 1).

Table 1. List of Case Study Countries and Reason for Study

Region	Country	Reason for Analysis
Africa	Kenya	Long-term Bank support for water resources development and management. Additionally, opportunity to learn for engagement in further work in Africa region.
Africa	South Africa	Acknowledged example of leading water resources policy and legislation and sound technical capacities. Additionally, opportunity to learn for engagement in further work in Africa region.
Africa	Tanzania	Long-term Bank support for water resources development and management. Additionally, opportunity to learn for engagement in further work in Africa region.
Middle East & North Africa	Morocco	Long-term Bank support for water resources development and management.
South Asia	India	Long-term Bank support for water resources development and management.

The case studies identify key policy and governance impediments and explore opportunities for groundwater management responses under different socioeconomic and physical settings. The case study reports were developed by consultants with extensive experience in the five countries.

Thirdly, best practices obtained from an analysis of non-Bank international groundwater experiences were used in the analysis chapters,[8] which also draw lessons from the case studies.

Intended Audiences

This report has two primary audiences:

[8] Chapters 4, 5, 6 and 7

- In recognition of the low profile of groundwater governance provision, this report aims to promote the concept more widely to Bank clients, external donors and partners, and a more general audience of academic and civil society organizations.
- More specifically, World Bank operational staff in the water sector, including water sector specialists, political economy and governance specialists, and in-country teams where water is a significant part of the Bank's engagement.

Dissemination and Learning
Knowledge management and opportunities for collaborative learning have been built into the study. To this end, dissemination and learning events will be organized, including:

- As part of the broader "Groundwater Governance: A Global Framework for Country Action" project with collaborative partners; and
- Specific regional training conducted for World Bank Task Team Leaders (TTLs).

1.4 Report Structure

This report is structured in seven chapters.

- **Chapter 1 – Background and introduction** – provides an overview of the status of groundwater resources and their need for improved governance. Given this imperative, the chapter outlines the report objectives, methodology, and structure as well as a synopsis of the Bank's portfolio of experiences relating to groundwater.
- **Chapter 2 – Governance and political economy** – defines the key concepts of governance and political economy and sets out the analytical framework used in the report.
- **Chapter 3 – Country case studies of governance arrangements** – provides a description of country case study governance arrangements. It presents the context and primary issues related to groundwater governance in the five case study countries. The governance issues highlighted from the case studies are further discussed in Chapters 4-6.
- **Chapter 4 – Constraints and options for setting good groundwater policy** - looks first (4.1) at the determining influence of context to explain why groundwater problems have emerged as they have and how context limits the governance response to those problems. This then provides a background for a discussion (4.2) of options and constraints for formulating responsive groundwater policy.
- **Chapter 5 – Governance at the strategic level** – examines three governance approaches (rights and regulatory approaches, the use of the incentive system, and subsidiarity and support to local water management) and assesses how a balance between these three approaches might be struck. There is a discussion of key implementation requirements, particularly the role of information, knowledge and communications and of conflict resolution mechanisms.
- **Chapter 6 – The role of participation and local collective management in good groundwater governance** - looks at the promising but vexed potential for improving outcomes through participatory and collective management approaches.
- **Chapter 7 – The way forward: towards improved groundwater governance –** starts (7.1) by illustrating two country cases where groundwater is an important resource and where governance reforms have been implemented in an attempt to improve outcomes in line with the nation's policies. On the basis of this implementation experience, the second part of the chapter (7.2) summarizes lessons and options and suggests how to select governance options appropriate to each situation, and how these options may best be operationalized.

2. Governance and political economy

In order to set the stage for this report, this chapter provides some definitions of concepts used, and then describes the analytical framework that has driven the presentation of findings from the case studies in Chapter 3, the analysis of constraints and options in Chapters 4-6, and the discussion in Chapter 7 of possible ways to apply the options.

2.1 Definition of Five Concepts Used

"Governance" is an elusive concept. Everyone has a general idea of what it means, but attempts at defining it do little to provide the layman a working grasp of what is meant. "Political economy" has an equally fugitive meaning in the minds of most readers. For this report, we propose simple working definitions of governance and political economy and of three concepts that also underlie the analysis; namely, subsidiarity, and the distinction between governance at the strategic level and at the local level. While these definitions may not be completely defensible or comprehensive, they are distilled from a wealth of literature (see Annex 2), and have guided the authors in writing this report. These definitions are:

Governance	The operation of rules, instruments and organizations that can align stakeholder behaviour and actual outcomes with policy objectives
Political economy	The way in which different stakeholders influence policy, governance and resource allocation, and thereby influence outcomes
Subsidiarity	Water management practiced at the level of the lowest feasible hydrological unit
Strategic level	The level at which decision makers decide policy, make laws, determine regulatory instruments, establish the incentive framework and set up and run agencies to implement these things
Local level	The level at which individuals, organizations and institutions determine actual outcomes in local water management areas and at the well head

2.2 Analytical Framework

The groundwater-specific analytical framework developed for this report is outlined in Figure 2. The framework is based on an extensive literature review and is a hybrid of different frameworks developed by Huntjens (2011), Huntjens *et al*., (2010, 2011a, 2012), Pahl-Wostl & Lebel (2010) and the OECD report on Water Governance in OECD countries (2011). Full details of the framework and its theoretical underpinnings[9] are presented in Annex 3.

[9] Related to context (including policy and legal and regulatory systems), governance capacities (including institutional arrangements, information management and communication, and financing / funding), and performance (including participation and capacity building).

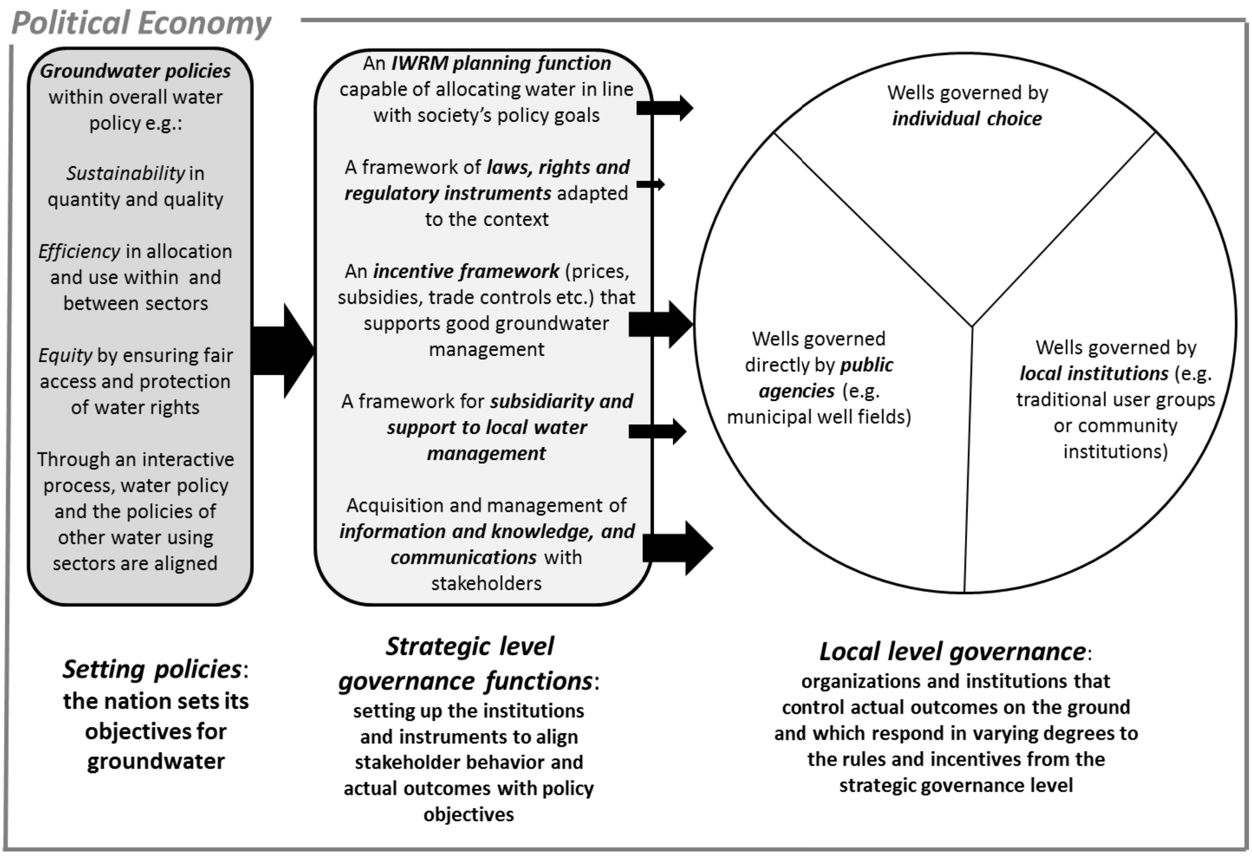


Figure 2. A Framework for Analysing and Assessing Groundwater Governance

The framework presented in Figure 2 distinguishes three parts of the groundwater governance system:

Setting policies refers to the processes by which a nation establishes its objectives for groundwater, integrates those policies with water, land and environmental policies, and aligns and harmonizes them with other related policies affecting groundwater (notably, agricultural policy, trade policy, regional and urban development policies, and policies on the division of public and private responsibilities, decentralization, and the role of stakeholder participation). The framework illustrates a paradigm ***good groundwater policy*** that might provide for:

- Sustainability in quantity and quality
- Efficiency in allocation within and between sectors to the highest societal value
- Equity by ensuring fair access and protection of water rights

Strategic level governance denotes the institutions and instruments designed by a nation to align stakeholder behaviour and actual outcomes with policy objectives. For the purposes of the simplified analytical framework, five components are distinguished:

- An IWRM planning function capable of allocating water in line with society's policy goals
- A framework of laws, rights and regulatory instruments adapted to the context
- An incentive framework (prices, subsidies, trade controls, etc.) that supports good groundwater management
- A framework for subsidiarity and support to local water management on a partnership basis,
- Acquisition and management of knowledge and information about the resource and its uses, and communications with stakeholders

Local level governance involves the organizations and institutions that control actual outcomes on the ground and respond (in varying degrees) to the rules and incentives from strategic level governance. This level includes, in descending order of responsiveness to strategic level governance:

- Public agencies (ministry branches, local authorities, basin agencies), which could be expected to more or less reflect policies and strategic level governance at the local level. These agencies may directly control part of the resource (e.g. municipal well fields) or they may influence outcomes by the application of a regulatory regime, or by working in partnership with local collective management institutions or with individuals.
- Local collective management institutions, including collective organizations; and rules, sanctions and dispute resolution mechanisms developed by communities and interest groups.
- Individual well owners, whose well development and abstraction behaviour is (in the absence of respect of any other governance system) determined by individual, household or family goals.

This framework was tested against all the elements in the literature and against practice, and it has proved fairly robust. The analysis in Chapter 3 is set out with this framework in mind, and Chapters 4-7 are organized according to this framework. Some aspects of governance (for example conflict resolution) that are not expressly listed have nonetheless been captured and are discussed within the framework.
Once a groundwater governance framework is in place, a variety of management instruments can be implemented (see Annex 4).

3. Country Case Studies of Governance Arrangements

This chapter presents the context, main issues and groundwater governance arrangements in the five case study countries: India, Kenya, Morocco, Tanzania, and South Africa. The chapter is structured to first identify the drivers and level of groundwater development in terms of both quantity and quality. Governance arrangements and issues at the policy, strategic and local levels are then identified. The governance issues highlighted in this chapter are discussed in detail in subsequent chapters of this report.

3.1 A Range of Contexts and Issues on Groundwater and Its Governance

Case studies in India, Kenya, Morocco, and Tanzania were selected due to the Bank's long-term support for water resources development and management in those countries, particularly its engagement on groundwater in India and Morocco. In addition, South Africa was selected because of the strength of its water resources policy and legislation, and sound technical capacities. In addition, the lessons learned there may be applicable to future Bank engagement in other countries in the southern Africa region.[10]

The country case studies illustrate situations ranging from over-development of groundwater beyond the sustainable yield (India) to groundwater in the very early stages of development (Tanzania).

These five countries illustrate a range of levels of development of groundwater, from India which has developed over one hundred percent of its sustainable yield, to Tanzania which has developed only 3 percent of its sustainable yield.[11] These countries also provide a range of hydrogeological settings.[12]

3.1.1 Drivers of Groundwater Development

Agriculture and water supply are the main drivers of groundwater development, but urbanization, mining and tourism also play an important role in groundwater use as well as in pollution of groundwater.

India

Millions of wells have been developed in India and two thirds of agriculture now depends on groundwater.

In India, there has been phenomenal growth in the exploitation of groundwater in the last five decades through the construction of millions of private wells. Irrigated agriculture has been the greatest beneficiary of the expansion (Figure 3). More than 60 percent of the irrigated area is now dependent on groundwater, and the sector is the largest user of groundwater, accounting for 91 percent of total groundwater volume withdrawals (Aquastat, 2010). Additionally, groundwater is a critical source of water supply, providing 85 percent of rural drinking water, along with an increasing share of urban and industrial water supply.

This rapid development has been driven by a combination of the availability of tubewell technology, government support and subsidies, and farmer preference for the inherent advantages of groundwater over other sources. The remarkable expansion in groundwater use in India has been prompted by a number of factors, including: (i) poor service delivery from public water supply systems, leading many farmers as well as rural and urban households to turn to their own private supplies for irrigation and potable use; (ii) new pump technologies and credit facilities, making the construction and operation of private tubewells affordable even for households with modest incomes; (iii) the independence, flexibility and timeliness of groundwater, which presented an attractive alternative to the technically and institutionally less responsive provision of surface water through public systems; and (iv) government electricity subsidies that have shielded farmers from the full cost of pumping, establishing a pattern of groundwater use that has proved very difficult to change (World Bank, 2010).

[10] Opportunities exist in Namibia, Mozambique and Zambia.
[11] In countries where the total national sustainable groundwater yield has not been exceeded, local cases of over-exploitation may still be evident.
[12] A summary matrix of regulatory and operational governance features of case study aquifers assessed against GW-MATE features is provided in Annex 5.

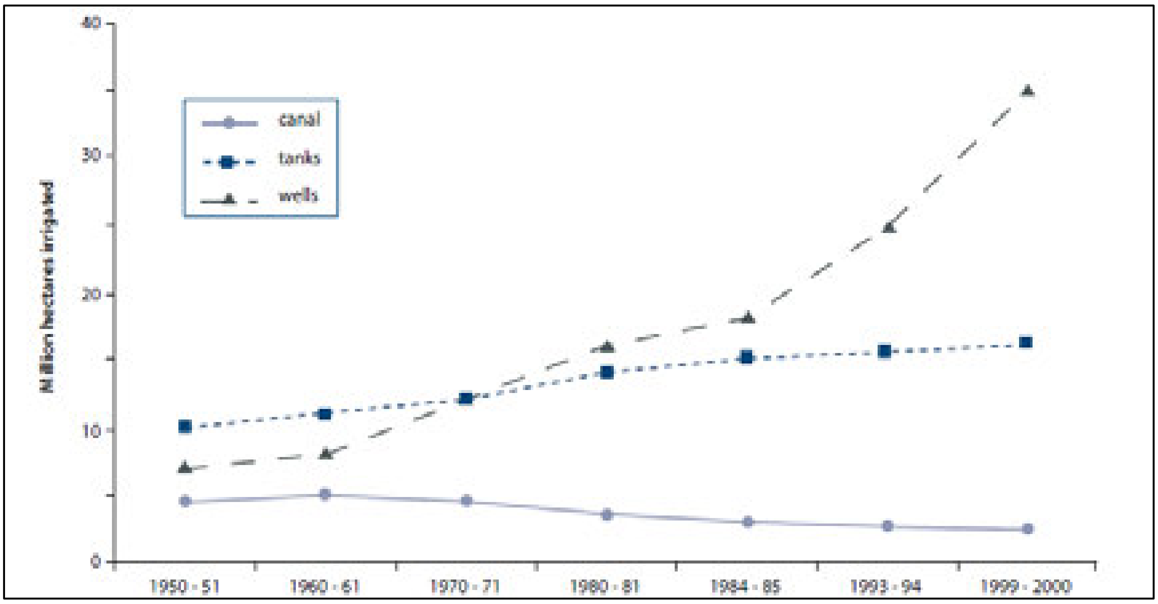


Figure 3. Evolution of Canal, Tank and Well Irrigation in India
Source: Bhatia, 2005, cited in World Bank, 2005d and World Bank, 2010e.

Morocco

In Morocco, groundwater accounts for 30 percent of overall water supply, including both irrigation and urban consumption (Bzioui, 2004).

In the two case study aquifers studied (Haouz and Souss), irrigation was far and away the dominant user, accounting for more than 90 percent of groundwater abstraction. Of this, two thirds is used for highly productive private irrigation schemes, and the remainder is used for lower value cereal crops. Both contribute considerably to national agricultural exports (Aquastat, 2000). In public irrigation schemes, the exploitation of groundwater resources has increased exponentially in many parts of the country for similar reasons to India; namely, easy access, reliable supply, and affordability. Additionally, several large cities depend partially or entirely on groundwater for their potable supply. Groundwater is the only source of water in many arid regions. Tourism, Morocco's third largest economic sector, is also placing increased pressure on groundwater resources, particularly in inland areas.

South Africa

In South Africa, agriculture accounts for two thirds (64 percent) of groundwater use, with municipal and rural water supply and mining requirements accounting for the balance.

Groundwater is also used extensively by the mining sector (DWA, 2010) and many rural districts have been served by groundwater resources in recent years, helping to ensure sustainable livelihoods for many communities. Some urban areas are already dependent on groundwater, while other major cities (such as Cape Town) are considering aquifer development to meet future demands.

Kenya and Tanzania

In Kenya and Tanzania, groundwater is mainly used for municipal and industrial supply. Groundwater plays a critical role in Kenya's economy. Reliance ranges from use as an increasingly important supplementary source for domestic, commercial and industrial purposes in Nairobi (which generates approximately 50 percent of national GDP) to almost complete reliance in the coastal tourist hubs and ports. Rural towns and communities are overwhelmingly reliant on groundwater for potable supply, particularly in the arid and semi-arid lands that account for 80 percent of national land area. In Tanzania, groundwater development has generally comprised shallow wells for domestic purposes in both rural and peri-urban areas where surface water supply distribution networks do not exist or are unreliable. Additionally, many urban areas exploit groundwater to augment supply from surface water sources.

3.1.2 Level of Groundwater Development and Emerging Problems

Over-abstraction of Groundwater in India and Morocco

In India, over-abstraction is becoming an increasing problem, already affecting almost one third of the resource.

On aggregate, India is withdrawing more than the estimated safe yield (Table 2). As a result, an increasing number of aquifers are reaching unsustainable levels of exploitation, with a 2004 nationwide assessment classifying the condition of 29 percent of groundwater blocks as semi-critical, critical or over-exploited. The potential social and economic consequences of over-abstraction are serious, as aquifer depletion is concentrated in many of the most populated and economically productive areas. Climate change will put additional stress on groundwater resources. For example, progressive reduction of the Himalayan glaciers is expected to lead first to a surge, then a decline, in associated base flows in the main Ganges tributaries, with consequent impacts on the extensive aquifer systems underlying the Ganges basin.

Morocco is beginning to experience problems similar to those of India.

In Morocco, the more intensively used aquifers, including the two case study aquifers, are overdrawn. In one aquifer, annual abstraction rates exceed the sustainable yield by almost 60 percent, resulting in a reduction in groundwater levels of about 40m over 20 years. The other aquifer studied has also suffered from a continuous drop in the water table since the early 1970s, with annual reductions since 2000 sometimes exceeding 2m/year over parts of the aquifer.

Table 2. Estimates of Current Groundwater Use

	India	Kenya	Morocco	South Africa	Tanzania
Gross national income per capita (US$)[13]	1040	730	2520	5820	440
Rainfall (mm)	2168	1063	426	520	1148
Pop density (people per km^2)	360	70	71	41	47
Groundwater availability (Mm^3/yr)	432,000 (renewable resource)	2,100	10,000 (renewable resource)	30,520	30,000 (renewable resource)
Safe yield (Mm^3/yr)	216,000 (est.)	1,040	5,000 (est.)	10,353	15,000 (est.)
Current usage (Mm^3/yr)	251,000 (withdrawal)	180	3,170	1770	460
Percentage use (%)	116	17	63	17	3

Note: Where safe yields are not known they have been set at 50 percent of recharge. Different terminology and methods of calculation mean that these data cannot be compared between countries.

Emerging Problems of Over-abstraction in Kenya, South Africa and Tanzania

Opportunities remain for further development in Kenya, Tanzania and South Africa, but a strong governance framework needs to be developed if the problems of over-abstraction and depletion are to be avoided.
In many countries, especially in Sub-Saharan Africa, there remain opportunities to develop groundwater resources further. Kenya, South Africa and Tanzania are currently using only small fractions of the estimated sustainable yields of many of their groundwater systems (Table 2). However, development needs to occur under a strong governance framework if issues of over-abstraction, pollution and degradation of recharge zones are to be avoided. For example, in Dar es Salaam, Tanzania, municipal water supply comes partly from a shallow coastal aquifer, which is vulnerable to sea water intrusion, and partly from the Ruvu River, whose base flow has recently decreased due to a combination of climate variability, catchment deforestation and use changes, as well as unlicensed upstream abstraction. The recently discovered deep Kimbiji aquifer provides a substantial opportunity for meeting the city’s water supply needs for the foreseeable future. If this groundwater resource is developed responsibly and managed in conjunction with local surface water sources, the city water supply could be assured for the coming decades and be well buffered against the uncertainties of climate change.

Already, some localized over-abstraction is occurring.

[13] GNI obtained from World Bank (2010d).

Although at a national scale many groundwater systems in these three countries are not under immediate threat, there are already cases of local over-abstraction. For example, in Kenya, the Nairobi aquifer system is over-abstracted partly due to a proliferation of unregulated private boreholes. The Naivasha Basin basal aquifer experienced over 14 m water level decline between 1999 and 2004 due to intensive abstraction for horticulture. In South Africa, two of the case study aquifers, the Dinokana-Lobatse dolomite aquifer and the Botleng dolomite aquifer, are considered to be at risk of over-exploitation. In Tanzania, over-abstraction is not a severe or widespread problem on a national scale, but groundwater levels in some aquifers underlying urban areas have been falling persistently.

3.1.3 Groundwater Quality Issues

In India, pollution and salinization are growing problems and arsenic contamination is emerging in some areas.

Groundwater pollution is more prominent in India than in the four other case study countries. India often contains concentrated clusters of polluting industries such as tanneries and textile mills, and the resulting pollution has, in an increasing number of regions, rendered the groundwater resource useless before it is exhausted. Pollution sources infiltrating into aquifers typically include: haphazard disposal of untreated urban and industrial wastes (such as discharges from tannery operations); faecal contamination due to inadequate sanitary arrangements as witnessed by extremely high nitrate levels in aquifers below cities that are intensively used for drinking water supply; and over-application of fertilizers, pesticides and insecticides on agricultural fields. Additionally, aquifers in arid and semi-arid regions are increasingly affected by salinity and over-pumping of coastal aquifers is leading to seawater intrusion. Arsenic contamination is problematic in some parts of India and has necessitated access to deeper uncontaminated sources. Likewise, high aquifer fluoride concentrations are widespread across about one third of India's districts.[14]

Pollution from agriculture and mining is also becoming a problem in South Africa.

Agricultural groundwater contamination sources in South Africa are most commonly nitrate-based, with fertilizers, pesticides, herbicides and growth hormones contributing to quality problems. Other groundwater contaminant sources include salinization from extensive irrigation, and infiltration of waters from mining activities (commonly referred to as "acid mine drainage.") Hexavalent chromium from chrome ore processing and radionuclide contamination from gold mining operations also pose threats to groundwater quality.

Although the problem is not yet widespread in Kenya, groundwater quality in some aquifers has been affected by agricultural, industrial and human pollution.

Point-source nitrate pollution has been recorded at livestock watering points, while high-density informal settlement is associated with bacterial contamination of groundwater beneath some major centres. Over-abstraction has also led to salinization of some coastal groundwater, and naturally elevated fluoride concentrations occur in groundwater along the Rift Valley belt. One study in 2009-2010 found that one third of boreholes supplying drinking water exceeded the national drinking water standard for fluoride concentration (1.5 mg/L), meaning that approximately 10 million Kenyans were potentially exposed to elevated concentrations.

To date, quality problems have emerged only locally in Tanzania

Generally, groundwater quality in Tanzania is acceptable for most uses, although there are problems of high salinity and high fluoride concentrations in some areas, and localized contamination in others. Salinity issues arise in coastal areas and in the central region where there are high evaporation rates and poor drainage. High fluoride concentrations occur in the north-east areas surrounding the Rift Valley system. Localized cases of pesticide and petroleum hydrocarbon pollution of groundwater have been reported. Widespread use of on-site sanitation in urban areas contributes significantly to the pollution of shallow aquifers, which is an important water supply source for the urban poor.

[14] 196 districts out of India's 640 districts and 19 states out of 28.

3.2 Governance Arrangements and Groundwater Management

The relation between governance arrangements and groundwater outcomes was assessed for all five case study countries. The analysis presented here follows the framework set out in Chapter 2, first assessing policy formulation issues, continuing with the strategic level governance functions, and finally discussing the operation of governance at the local level.

3.2.1 Policies for Groundwater and Alignment with other Sectoral Policies

Alignment of Policies on Groundwater Abstraction and Use

In all countries studied, several sectors were vying to abstract groundwater and were consequently having an impact on or benefiting from groundwater resources. The most widespread use is in agriculture, particularly in India and Morocco, but mining development, urbanization, and tourism are also important drivers of groundwater development and pollution. *There is a clear need for a harmonized policy framework to coordinate water resources policy with the policies of the water using sectors*.

In practice, however, the alignment of policies regarding groundwater has yet to be achieved in any of the five case study countries.[15] There are many examples where sectoral policies, at best, hamper good groundwater management and, at worst, jeopardize the resource. In India, the sectoral linkage between groundwater use and power policies that provide electricity to farmers at a heavily subsidized flat tariff is so prominent that it is referred to simply as the "energy-groundwater nexus." In a nutshell, water resources policy in India aims at groundwater conservation and sustainability, while agriculture and energy policies are driving in the opposite direction, creating strong incentives to over-abstraction.

Part of the problem is organizational, with no mechanisms to align water policy and other sectoral policies.

In Morocco, there is a lack of effective coordination of the water sector with other sectors (agricultural, urban, etc.), which affects water resources, including groundwater. Current policies are characterized by a predominantly vertical sectoral approach with serious deficiencies in terms of horizontal coordination between the water sector and other sectors. For example, responsibility for water resource management lies with the river basin agencies under the water ministry, while the heaviest water using sector – irrigated agriculture – is under the jurisdiction of the agricultural ministry. Moreover, inter-sectoral mechanisms to coordinate policy and planning are not systematic. For example, although the water ministry participated in discussions about the *Plan Maroc Vert*, this has not led to a systematic alignment of policies. The lack of mechanisms to align policies on groundwater underlies many of the impediments to groundwater management, to the point where the Moroccan case study states that "intersectoral policy coordination .... is the weakest link of the entire groundwater governance chain."

The problem is well recognized in all five countries but, so far, it has been beyond the capacity of the governments to achieve the necessary harmonization of policies. For example, although the Kenyan draft Groundwater Protection Policy proposes that a National Standing Committee be established to deal with cross-sectoral issues under the guidance of the ministry in charge of water affairs, no action has yet been taken.

Alignment of Policies on Groundwater Pollution Prevention and Protection of Recharge Areas

The cross-sectoral linkages needed for policies on groundwater pollution prevention and protection of recharge areas were weak in all case-studies

These policies affect a wide range of stakeholders, including land use planners, industrial and mining enterprises, and local governments, all of whom have limited incentives to protect groundwater. In Kenya and Tanzania, there is a very limited understanding of the land surface-groundwater linkage among professionals of the relevant sectors and, as a consequence, there is no strategic awareness of the need to protect groundwater resources. In both countries, there are examples where local councils have granted approval for developments that have jeopardized recharge areas, partly because of a lack of information, and partly because councils do not possess any groundwater expertise and do not understand the importance of protecting recharge areas (see Box 1). In

[15] There are some partial exceptions such as the use by the Tanzanian government of the Lands Act to control rapidly increasing groundwater pollution in an important aquifer. However, it should be noted that this is the exception rather than the rule.

South Africa, sectoral integration is limited by lack of cooperation and coordination among government agencies even though the National Environmental Management Act is supposed to guide such integration.

Box 1. Groundwater and Land Use Planning in Kenya and South Africa

Kenyan law does not provide for groundwater to be taken into account in land use planning.
Groundwater Conservation Areas in Kenya are linked to land use planning and therefore related to other legislation like the Physical Planning Act and Environmental Management and Coordination Act. However, analysis shows that neither act makes specific mention of the conservation of groundwater resources as a relevant consideration in formulating physical developments plans and environmental planning. This is a particularly acute problem with respect to the Nairobi Aquifer System, which is subject to intense exploitation. To date, the only physical plan that has been prepared is for the Karen Langata area of Nairobi. Though gazetted, it is not officially recognized by the City Council of Nairobi and therefore has not been enforced.

In South Africa, provisions such as the polluter-pays principle have been established to protect groundwater from pollution from mining, but they have not yet been implemented. The discharge or decant of contaminated water and highly saline effluents from mining activities and/or abandoned mines is a serious environmental threat and social concern. In particular, acid mine drainage from gold mines in the Witwatersrand area and coal mines in Mpumalanga need urgent attention, but the problem has not been addressed despite the fact that South African legislation governing mine closures requires the rigorous mitigation of both biophysical and socioeconomic impacts.

Source: Mumma *et al*., 2011; Pieterson *et al*., 2011.

3.2.2 Governance at the Strategic Level

Laws, Rights and Regulatory Instruments

The country studies concluded that, in general, laws, rights and regulatory instruments governing groundwater were well designed but that improvements were possible and – most importantly – implementation was a major challenge.

According to the stakeholders consulted during the study, all five countries have formal governance arrangements that, while open to improvements, should provide a framework for groundwater management. These arrangements included provisions for groundwater quantity and quality monitoring, drilling permits and groundwater rights, tools to reduce groundwater abstraction, and stakeholder participation. Some countries also impose sanctions on illegal well operation, groundwater abstraction charges, land use controls over polluting activities, and levies on polluting discharges. Basin authorities are in charge of implementing most of the activities related to groundwater in Morocco, Tanzania and South Africa, while groundwater governance in India and Kenya relies on national or state authorities.

However, stakeholder consultations also identified gaps in these arrangements. For example, they stated that Moroccan policies could include more emphasis on demand management, and that the governance frameworks in Tanzania and Kenya place disproportionate emphasis on surface water management, a bias reflected in implementation with regard to financing, staffing, planning, and execution of water management. Nevertheless, in all the countries, stakeholders considered that the fundamental problem was not the inadequacies of governance frameworks but difficulties in implementing the policy as well as legislative provisions that impede good groundwater governance and management.

Although India historically had a strong framework and effective enforcement capacity for top-down groundwater planning and regulation, it is now eroding. In addition, public organizations are not adapting readily to new approaches in support of local collective management.
India is also the only country studied that has established specific organizations for groundwater governance. These are: the Central Ground Water Authority (CGWA), which is responsible for groundwater regulation, and the Central Ground Water Board (CGWB), which is responsible for research, resource assessment and monitoring. However, despite this framework and the country's centralized command and control reflex, the proliferation of tubewells during the "groundwater revolution" has greatly increased the challenge of regulation. While these organizations manage to slow down the drilling of new wells in over-exploited areas, they have few

tools to influence groundwater use by existing wells. The approach is now being further impeded by lack of implementation capacity, particularly a pronounced lack of the needed specialized groundwater staff at both central and state levels. The Indian case study report found that "…generally, technical, legal and institutional provisions are in a more or less acceptable status but implementation capacity is rather weak." Additionally, where available, staff skill sets continue to be oriented towards groundwater development rather than to the socioeconomic dimensions of groundwater use that are key to effective groundwater governance. Even states such as Andhra Pradesh and Maharashtra, which boast the best groundwater departments in the country, have inadequate staffing strengths and profiles relative to what is required.

The same is true in South Africa where legal changes have been introduced to recognize water rights and to require their regulation, but the capacity to implement the regulatory framework is weak.

South Africa's Water Act requires that licenses for water use be assessed and approved. Lack of implementation capacity to deal with the large number of licenses created a significant backlog, which then prompted introduction of a simplified procedure to address it.[16] The lesson from these experiences is that apparently good governance arrangements need to be matched with implementation capacity.

Most laws and rights systems define water as public property and require licensing, but this approach diverges widely from popular perception and from actual practice.

In South Africa and Tanzania, water laws clearly state that ownership of both surface and groundwater is vested in the state and that land owners must acquire a license to use the groundwater. Despite the fact that the law is clear, there are difficulties in putting it into practice because of the lack of acceptance on the part of stakeholders and the capacity constraints discussed above. In South Africa, for example, the case study laconically records that "…social views of groundwater [ownership] lag behind the formal policy of a public resource, and are tied more closely to land ownership."

In Kenya, while statutory provisions now vest ownership and regulatory powers in the state and supersede the common law right of landowners to access and abstract groundwater beneath their land, decisions on how much water to abstract are still, in practice, left to landowners to make, reinforcing the perception that groundwater is a private good.

In India, groundwater has also traditionally been seen as following the right to land, based on the Indian Easements Act of 1882. In 1996 the Supreme Court instructed the government to establish the CGWA to regulate and control groundwater development. There is now an emerging understanding of the public interest dimension of groundwater, thanks to specific awareness-building campaigns in areas such as Andhra Pradesh.

Delegating Groundwater Management

The capacity problems of local governments have been apparent where attempts were made to decentralize planning and management of groundwater to local authorities.

Local government lacking in groundwater expertise have often delegated responsibility for land use planning and for management of borefields for municipal supply. For example, there was no local government in South Africa that had its own groundwater expertise, and 74 out of 231 local authorities did not employ external technical experts (MacKay & Koster, 2005), despite often facing serious groundwater management problems. Similarly, local Kenyan authorities employed planners but no hydrogeologists and, hence, their ability to adequately address groundwater issues was severely limited. However, larger urban water authorities in Kenya and Tanzania did have better access to groundwater expertise. Some, such as the Dar es Salaam Water and Sewerage Company DAWASCO in Tanzania, have hydrogeologist technicians on staff while others hire consultants.

[16] In addition to the case study examples, Peru also faced similar administrative burdens related to the development of a register of water users.

Information, Knowledge and Communications

Information for Groundwater Management

In general, knowledge of aquifer characteristics and exploitation was weak, and this certainly undermines capacity to manage the resource. One recent study of groundwater in Africa (AMCOW 2012) found that "…poor data or inadequate availability of water-related data and inappropriate water information systems" were a major constraint in most of the countries surveyed.

Although basic information on hydrogeology is available, it is often insufficient for detailed planning and management.

With the exception of some aquifers in Kenya and Tanzania, hydrogeological maps suitable for management were available for all the aquifers studied. Tanzania did have access to maps produced by the Southern Africa Development Community (SADC), although they lacked sufficient detail required for management purposes. Information beyond basic hydrogeology is less available. The only aquifers that are adequately delineated for management are the two Moroccan aquifers, the Botleg, Steenkoppies and Bapsfontein aquifers in South Africa, and the Makutupora aquifer in Tanzania.

In addition to knowledge about the groundwater resource itself, groundwater management requires information about its uses. Updated and systematic information about groundwater abstractions for different uses is often lacking and, in most countries, groundwater use is estimated using indirect methods.

In Kenya, resource assessment is at an early stage, and users have virtually no access. A lack of knowledge about the national aquifer systems is also an issue. This is not due to inadequate technical ability, but to limited resources available for conducting the kind of assessment needed, coupled with the complexity of some of Kenya's aquifer systems.[17] Without this information, the ability of managers to regulate pumping, polluting activities and inappropriate land uses is severely restricted.

In Tanzania, information on groundwater is sparse and rarely available. The little data that is available (from past studies and regional water master plans) is not easily accessible or has not been digitized. Furthermore, there is generally inadequate data and knowledge on groundwater resources (static levels, yield, quality, etc.). Aquifer delineation is low or not in place, further hampering management efforts.

There is even less information available on critical aquifer characteristics, such as recharge rates and transmissivities, since these require specialist investigations and modelling. Where some aquifer characteristics are available, as in all four Tanzanian aquifers, it is often as part of externally funded development projects or as a result of localized consultancies and academic studies. Only two Moroccan aquifers had groundwater models available that managers were able to use. Models are generally unavailable in the other countries studied. Moreover, in the aquifers where they do exist (for example, Steenkoppies and Dinokana-Lobatse aquifers in South Africa) there is limited capacity to use them.

Information on groundwater quality is also highly variable.

There have been some assessments of groundwater pollution in the case study aquifers, but these assessments have typically been limited to a small number of pollutants or just a portion of an aquifer. For example, in Tanzania there are very limited studies on groundwater pollution from agro-chemicals even though these chemicals have been used for decades with limited control.

In discussing the South African aquifers, the case study authors made the important point that, even if there are deficiencies in knowledge, there is often enough information available to make management decisions. *The real shortcoming lies in the lack of human capacity to implement these recommendations and decisions and the limited political will to take action*.

Monitoring

The essential complement to aquifer characterization is subsequent monitoring, and this is generally a weak point.

[17] The Nairobi Aquifer Suite is a case in point; it comprises numerous unconfined and confined beds of lava, old land surfaces and lake beds, which in boreholes that are deep enough may amount to as many as five separate aquifer units.

Some of the most heavily used aquifers do not contain monitoring programs, which are a fundamental requirement for effective management. All case study aquifers, except the Baricho (Kenya), Babati (Tanzania) and Arusha (Tanzania) aquifers, are subject to either widespread or localized over-abstraction. Of these, the Makutopora (Tanzania) aquifer has a satisfactory aquifer-wide groundwater level monitoring program and others, such as the aquifers in the Indian states of Maharashtra and Kerala, the two Morrocan aquifers, the Botleg aquifer (South Africa) and the Arusha aquifer (Tanzania), have adequate monitoring programs. Conversely, some of the heavily used aquifers, such as the Nairobi,[18] Steenkoppies and Dar es Salaam aquifers, have only weak or nonexistent aquifer-wide monitoring programs. Other regional monitoring programs rely on water levels from production bores, a practice that can lead to considerable data inaccuracies.

Water quality is not always adequately monitored, but several countries are working hard on improvements.

Urban water authorities, such as the Dar es Salaam Water and Sewerage Authority (DAWASA) in Tanzania that draw on the aquifers for water supply, usually maintain their own water level and water quality monitoring programs to check health-related parameters. Similarly, the Makutopora aquifer (also in Tanzania) has a satisfactory groundwater quality monitoring program. However, some aquifers with serious water quality problems, such as the Houdenbrak and Bapsfontein aquifers in South Africa, have experienced a reduction in groundwater quality monitoring programs, despite serious nitrate contamination issues. Reasons cited for this decline in monitoring include difficulties in gaining access to monitoring boreholes, lack of budget for rehabilitating monitoring boreholes, and lack of field staff to carry out monitoring.
Countries are well aware of the need to improve groundwater monitoring. Recent groundwater monitoring programs have included:

- The Department of Water Affairs in South Africa has trialled the Groundwater Resource Information Project (GRIP) in Limpopo province to gather data on groundwater (Box 2).
- In Kenya, the Water Resources Management Authority recently instituted a systematic monitoring program that targets most of the important Kenyan aquifers. Water level and quality trends will be collected quarterly, except for intensively-utilized aquifers where data will be collected monthly.
- The Water Quality Assessment Authority (WQAA) in India has strengthened the water quality monitoring capacities of states by establishing standardized monitoring protocols and facilitating the creation of state-level Water Quality Review Committees, which review and interpret state water quality data. In addition, the World Bank-funded Hydrology Project has led to major improvements in water quality monitoring in nine states, although additional work remains to reach satisfactory quality standards.

Box 2. The Groundwater Resource Information Project (GRIP) in South Africa

In South Africa, the Groundwater Resource Information Project (GRIP) has gathered enough information to allow integrated water management to be implemented all across Limpopo province.
GRIP is a project of the South African Department of Water Affairs whose aim is to improve data holdings by accessing unpublished or “private” data as well as new groundwater data collected by visiting boreholes in the field, particularly those in priority areas. It is planned that all GRIP data be entered into the DWA national WARMS database. GRIP will also develop systems and procedures for the collection and verification of unpublished data.

To date, GRIP has been fully implemented in Limpopo province, where it began in 2002. More than 2,500 villages have been visited in the province, 15,500 borehole sites have been verified, and 1,500 pumping tests have been added to the provincial database. Limpopo province probably now has the most extensive and best verified dataset on rural groundwater resources in the country, and enough is known about groundwater in the province to allow it to be much better integrated into general water resource management. The extra data has led to a higher borehole drilling success rate in the province, saving a considerable amount of money.

Source: Pietersen *et al.*, 2011.

[18] Twenty monitoring boreholes are currently being organized by the Water Resources Management Agency in the Nairobi Aquifer System with water levels being collected monthly.

Access to Information
Access to monitoring records varies across the countries studied.

South Africa is well served through the recently developed National Groundwater Archive which allows users to upload data remotely. This central database will be strengthened further through the GRIP program (see Box 2). In Tanzania, data is accessible only upon request from the Basin Water Offices. While local data retained at the Basin Water Offices may be accessible to water user associations and local groundwater managers, lack of integration for use at higher levels hampers national strategic assessments and policy development. In Kenya, the draft National Groundwater Policy calls for a national groundwater database, but the database has not yet been established. Most data is retained by the collecting agency, such as an urban water authority, and while theoretically it remains available, in reality it may often be difficult or impossible to obtain. In Morocco, information from groundwater monitoring networks in the Haouz and Souss aquifers is published in periodic reports that are publicly available and accessed via the Internet.

Communicating Information and Knowledge
Generally, there are significant problems over information-sharing that reinforce misperceptions about groundwater as an inexhaustible resource.

Even where information exists, information asymmetry often constrains its exchange between different stakeholders. For example, information is typically not in a form that is easily accessible to decision makers or the public. In cases where relevant information ***is*** available, there is often ineffective exchange of that information between stakeholders. Ultimately, this ineffective information exchange contributes to the long-standing perception that groundwater is an inexhaustible resource that is the property of the overlying landowner.

India carries out an annual assessment of the groundwater balance within the nearly 6,000 groundwater blocks. This has been an essential tool in mapping groundwater conditions and creating awareness among decision makers. One of the limitations of this system, however, is that the units used for the groundwater assessment exercise are administrative units, mostly at the sub-district level, without any link to physical boundaries.

Capacity Issues: Limited Capacity and Skills in Organizations
Staff and capacity for implementing groundwater plans and regulations are generally weak and deteriorating.

In all case study countries, the central and regional institutions typically lacked the skills and capacity to carry out their roles adequately. Furthermore, in some cases, institutions struggled to maintain their already limited capacity for implementing water policy and legislation.

- In South Africa, a reorganization of the Department of Water Affairs (DWA) led to the dissolution of the Directorate of Geohydrology and the integration of groundwater staff into other directorates. This restructuring left the department without a critical mass or central coordinating point for groundwater management. More generally, staffing challenges were exacerbated by an ageing workforce, emigration of skilled workers, and attraction to higher paid sectors such as mining. The DWA recorded general staff vacancy rates of 50 percent in geotechnical and hydrogeological positions. Within the directorates, for example, in the Directorate of Hydrological Studies, vacancy rates for similar jobs were as high as 70 percent and 66 percent respectively.
- Similar deficiencies were evident in the Tanzania Ministry of Water, where vacancy rates for hydrogeologists and technicians were 55 percent and 40 percent respectively.
- The scale of the human capacity challenge was also illustrated in the Kenya WRMA, which employs only one hydrogeologist in its headquarters and one in each of its regional offices.[19] Yet, the WRMA is required to police more than 4,000 groundwater permits in the Nairobi sub-region alone and about 1,200 permits in the Lake Victoria South region.
- In Morocco, the recent departure of many senior administration executives and staff (both at headquarter and basin agency level) proved a major handicap for the implementation of groundwater management action plans.

[19] Apart from the Nairobi sub-regional office where there were two

In general, not enough new technical staff and specialists are being trained.

All five case study countries have tertiary institutions where degrees are offered that include groundwater-related units, as well as other institutions where technical staff can be trained. Nonetheless, all case study reports state that there are inadequate numbers of graduates to meet national needs. The Morocco case study also states that there are insufficient programs for training staff already working in the sector.

In all countries studied, there were inadequate budgets to implement the governance framework.

Funding remains an impediment to implementing governance arrangements. South Africa, Tanzania, Kenya and Morocco all report shortfalls in operational budgets for groundwater management, or where surface and groundwater budgets are not separated, for water resources management generally. In some cases, this was because the agencies involved were supposed to finance their operations from the regulatory fees collected, and they were not able to collect enough. In Kenya, for example, the Water Resource Management Authority (WRMA) receives no allocation from the Treasury, and in 2009-2010 collected less than Ksh 400 million (US$4.8 million) of its budgeted expenditure of Ksh 639 million (US$7.7 million) from water use fees.[20] This translated into a 37 percent budget deficit. Likewise, the Morocco basin agencies also had budget shortfalls, although their deficit was covered by the national government. The situation is somewhat better in South Africa because water resource management activities are mainly funded through revenue from charges collected by the Water Trading Entity (WTE), and from allocations from the government's Exchequer Account. While the WTE has generated sufficient income to meet its operating costs, it has been unable to make budgetary provision for the maintenance or rehabilitation of existing assets because the agricultural water charges are insufficient to provide for such cost recovery.

3.2.3 Governance at the Local Level

Low Enforcement of Regulatory Measures

Four locally relevant regulatory measures are analysed here: control of groundwater abstraction, prevention of pollution, protection of recharge zones, and control of borehole and well development. All five countries have difficulties in implementing the regulations.

Control of Groundwater Abstraction

All countries studied are trying to implement top-down regulatory and licensing approaches, but implementation is very slow and the impact on resources is hard to detect.

Three of the five case studies (with the exception of India and Morocco) demonstrate only weak or completely deficient tools for controlling groundwater abstractions at the local level (Annex 5). Only the Souss Massa River Basin Agency in Morocco has developed a formal agreement with groundwater users at the local level (Box 3), although whether this will work in practice remains to be seen. Beyond the Souss Massa basin, there is a lack of acceptance by irrigators of the provisions of the legislation on groundwater abstraction. In the Haouz aquifer, the tools are available but the water institutions lack the capacity to use them.

In India, over-abstraction is driven by the perverse energy incentive that makes it difficult to enforce controls on groundwater abstractions. In Kenya, groundwater users are required to self-assess the quantity of water used, with the consequence that most groundwater users are believed to take water in excess of their license conditions. Finally, in Tanzania, water user permit requirements are gradually being implemented and wastewater discharge permit requirements are gradually being recognized, but implementation is still far from satisfactory.

Pollution Prevention

The case studies show a widespread inability to control activities that pollute groundwater (Annex 5). South African legislation requires waste discharge permits, but the system for implementing them has not yet been established. In the Steenkoppies aquifer, for example, there is little capacity to levy fees on pollution discharges. Similarly, in Tanzania, the enforcement of discharge permits is very poor, and mostly limited to large wastewater producers from industry and urban water authorities. In India there are adequate instruments provided in the

[20] Chiefly from corporate and industrial users only

law to control groundwater pollution for *point-polluting activities* but these do not address *large scale diffuse pollution* by agricultural chemicals or through lack of sanitation.

Box 3. Aquifer Management Contract Approach in the Souss-Massa Area in Morocco
The Souss-Massa River Basin Agency developed groundwater management action plans and incorporated the main provisions of the action plan into a framework convention signed by key regional stakeholders in the water sector. This convention specifies the responsibilities of stakeholders and their financial contribution to funding the action plan. These measures have been discussed and agreed upon by the agency and the key regional stakeholders and include: (i) approval of simplified procedures for delivering well/borehole drilling permits and abstraction licenses; (ii) organization of the drilling profession; (iii) water conservation measures; (iv) restrictions on new irrigation development; and (v) awareness building and communication. These measures limit new entrants and provide incentives to current users to sign on to contracts in order to be formally recognized as users and become eligible to receive support for water conservation measures. Implementation of the contract approach is in its initial stages; hence, it may be too early to judge results. While this convention is an innovative approach to implementing the plan, it has two main shortcomings in its present form: (i) it is signed by high-level farmers' organizations without direct involvement of actual water users and so may prove difficult to enforce; and (ii) the convention includes strong commitments from the state without equivalently strong commitments from the farmers' organizations. Source: FAO, 2009.

Also, the capacity to use these instruments is weak. Tannery wastes, for example, are being contained through measures such as common effluent treatment plants but the technology has not been widely adopted due to cost restraints. Morocco demonstrates some positive results: While pollution cannot be directly controlled under Morocco's Water Law by the river basin agencies because of implementation difficulties, other laws are used to check groundwater pollution, including environmental legislation and solid waste management legislation.

Protection of Recharge Zones

Controls over land use activities and protection of recharge areas are lacking in most of the countries. Such protection at the terrestrial interface may help protect the long-term quantity and quality of aquifer recharge at the source of replenishment. In Morocco, controls are available but there is little capacity to implement them in the two catchments studied. Similarly, in South Africa, protection of recharge zones is included in some national instruments such as the National Groundwater Strategy[21], but the reality is that there is little practical ability to carry them out. However, the protection of the recharge area of the Makutopora aquifer in Tanzania from pollution illustrates that, when there is sufficient political will, obstacles to management can be overcome. Such land use control may help promote the sustainability of groundwater utilization and reduce the need for costly (and sometimes ineffective) quality remediation interventions.

Control of Borehole and Well Development

The regulation of drilling activities and new boreholes is included in the water legislation of South Africa, Tanzania, Kenya and Morocco, but these provisions are difficult to enforce. In Morocco, the agencies in the two basins studied have only a weak capacity to implement these provisions or to take action against illegal well operations (Annex 5). In South Africa, only one of the 19 case study aquifers (Steenkoppies) has an acceptable capacity to implement the required provisions. The South African case study concludes that "…instruments to prevent well construction and sanctions for illegal wells are non-existent." The Tanzania case study also concluded that the guidelines governing the private sector well-drilling industry have been ineffective.

[21] The National Groundwater Strategy states that "Land-use planning has to consider groundwater resources as a precious and finite resource, and take all necessary measures to protect groundwater resources and their recharge mechanisms in the long run."

Alternative Approaches Through Participation and Collective Management

Examples of Local Collective Management

Local water management and self-regulation are good alternatives or complements to top-down regulation.

The case studies suggest that, in some circumstances, increased participation of local collective management institutions may be more effective than regulation. The example of Hivre Bazar village in India (Box 4) illustrates what can be achieved through active user participation in rule enforcement.

Box 4. Self-organized Groundwater Management in India Conserves the Resource, Improves Incomes and Increases Land Values

Hivre Bazar village in Maharashtra state has a long history of drought and land degradation. In the most favourable years almost 60 percent of the land can be irrigated, but in drought years wheat and summer crops have to be radically reduced.

A concerted effort on groundwater management began in 1994 under the leadership of an informed and charismatic Village Council Chief. The Village Council decided to cooperate to maximize benefits from existing groundwater. They prohibited expansion of borewells for agricultural irrigation, undertook comprehensive reforestation and water harvesting, and banned sugar-cane cultivation because of its high water use.

Most importantly, in 2002 the Council introduced crop-water budgeting at the level of the village. In dry years villagers are asked to reduce their proposed irrigated area and to grow low-water demand crops, with mutual surveillance usually being enough to achieve compliance. No change in groundwater abstraction rights is implied – the community merely controls access to groundwater and advocates which crops can be irrigated.

Such proactive groundwater management has resulted in a marked contrast between Hivre Bazar and most surrounding villages. At the household level, the benefits of community land and water management have meant a marked increase in household incomes (to over US$500/yr on average) and the appreciation of land values in the past 15 years.

Source: Garduño *et al*., 2011; GW-MATE Case profile No 22.

In all the countries studied, there were examples of local people organizing themselves for groundwater management, with or without government help:

- The community in Tabata, Ilala District in Dar es Salaam City, Tanzania, developed groundwater sources and managed them without government assistance.
- Another well-developed groundwater-based community water supply system in Dar es Salaam, Tanzania, is the Kwa Ngilangwa scheme in Mwananyamala ward, established in July 2005 through the formation of a Water User Association (WUA).
- In Kenya, Groundwater Resource Users Associations remain uncommon, although two groundwater-specific Water Resource User Associations (WRUAs) are being established in the Baricho and Tiwi regions.
- The example of Hivre Bazar village in Maharashtra state in India (Box 4) provides a striking example of how a self-organized WUA can bring about improvements in groundwater management when the social structure and the hydro-geological conditions are favourable. The Hivre Bazar example also illustrates the powerful effect of individual champions who can lead and direct stakeholder involvement. However, a limitation to this approach may be whether it can be scaled up to larger groundwater systems.

Examples of Public Sector Support to Local Collective Management

Participatory and collective management approaches have been greatly strengthened by the sharing of information and by capacity building.

Building an understanding about the special characteristics of groundwater among its users, as well as among those whose actions have an impact on groundwater (through, for example, polluting activities), is a first step towards effective stakeholder participation. The Kenya case study notes the importance of targeted sensitization and education programs because groundwater users generally have a very poor understanding of their responsibilities for managing the common resource. Unfortunately, the case studies do not provide any good examples of systematic educational programs. Lack of community knowledge is often compounded by a similar lack of expertise within local governments. No local government in South Africa has its own groundwater expertise. Similarly, most Kenyan local authorities employ planners but no hydrogeologists, although larger urban water authorities have better access to groundwater expertise.

In some cases, public services have become the community's partner in awareness-raising.

The government of Tanzania provided training to the community-based organization managing the Kwa Ngilangwa groundwater system. In Morocco, the basin agencies organize awareness building campaigns to familiarize groundwater users with the risks of overexploitation and groundwater pollution by agricultural activities and wastewater dumping. However, these campaigns were limited (JICA, 2007).

Although these steps towards supporting local collective management are so far tentative, there is evidence that this is an effective path in certain circumstances.

Overall, the case studies suggest that regulation often proves difficult for reasons of capacity and non-acceptance by stakeholders. There is evidence that groundwater governance can sometimes be delegated with a focus more on enabling users to manage interactions among themselves rather than promoting a one-way, top-down management hierarchy. However, to date in the five case study countries, support to the decentralized stakeholder-driven approach is still weak. Annex 5 suggests that the level of public sector/stakeholder cooperation in groundwater management in the five countries ranges from inadequate to weak. Nonetheless, some exceptions in specific aquifers demonstrated adequate capacity for public/stakeholder partnership, indicating some gradual achievement of progress.

Indeed, working models of community-based groundwater management in partnership with public agencies have been successfully promoted in Andhra Pradesh, India, for almost twenty years.

With the support of local NGOs, Andhra Pradesh has pioneered for almost two decades the promotion of community-based groundwater management through different projects, including World Bank-financed initiatives (Garduño *et al*., 2009). For example, one of the projects involved farmer communities in a program of groundwater education and monitoring using simple devices and methodologies. Farmers then engaged in discussion on how best to arrange their cropping patterns. Although most of this experience remains at the pilot-project stage, analysing the conditions for success could suggest lessons for replication.

If community-based management in partnership with public agencies is an indicated route, this requires policy decisions, an enabling legal framework, and specific arrangements for support.

Although several of the collective management examples studies did not receive government support, they all needed to operate within a framework of country laws, regulations and water strategy that recognize, or at least accept, community participation and collective management as legitimate, and provide a necessary measure of support, such as information on aquifer characteristics.

* * * * *

Summary of Main Findings from the Case Studies

The case studies have provided a rich variety of lessons, and many of these lessons were shared by several or all of the countries studied. All countries and study areas were suffering depletion and quality deterioration of the aquifers to a greater or lesser degree. All five countries had policy frameworks in place, but groundwater policies were generally poorly articulated with those of the water-using sectors, particularly agriculture. Formal governance arrangements were largely top-down, although with some decentralization to basin level and some moves towards partnerships with local collective management organizations. However, everywhere the rights and regulation approach to governance was proving not well adapted to the fast changing realities of the "groundwater revolution," and everywhere implementation capacity fell far short of the ambitious regulatory provisions.

Information on aquifers and on groundwater use was generally weak, although adequate for management approaches to be determined. Information sharing was everywhere poor, and systematic communications programs were rare. Public agencies in general lacked staff and resources, were under-financed, and lacked the capacity to do an adequate job.

At the local level, there was a big gap between the regulatory regime and facts on the ground. Rules on drilling and abstraction, on pollution and on protection of recharge zones were little applied. Some initiatives to delegate management to the basin level appeared more promising. At the local level, there were a number of interesting examples of collective management and self-regulation, even though these were weakly embedded and not strongly linked to public sector support structures.

These experiences and the issues arising provide the main empirical base for the analysis of issues and options in the rest of this report.

4. Constraints and Options for Setting Good Groundwater Policy

Chapter 3 presented a rich set of actual results in groundwater that underlined the scale and scope of real problems in groundwater management–particularly the increasing rates of depletion and the growing water quality problems – and the relatively poor performance of the governance systems in place to contain these problems.

The case studies highlighted some gaps between the ideal framework implied by the chart in Chapter 2 and the actual governance arrangements in place in the five countries. In some cases, the governance arrangements represented a paradigm which was poorly adapted to the reality of millions of wells pumping away oblivious of the regulatory regime they were supposed to be respecting. In other cases, the governance regime might have been implementable but the well-resourced, highly competent agencies needed to implement it did not exist. The rest of this report is therefore devoted to trying to define governance options adapted to the reality of the groundwater challenges, and to the political, social, budgetary and economic context in which those options have to be applied.

The present chapter on <u>groundwater policy</u> looks first (4.1) at the determining influence of context to explain why groundwater problems have emerged as they have and how context limits the governance response to those problems. This assessment then provides a background for a discussion (4.2) of options and constraints for formulating responsive groundwater policy.

Chapter 5 on <u>strategic level governance</u> then examines three governance approaches (rights and regulatory approaches, the use of the incentive system, and subsidiarity and support to local water management) and assesses how a balance between them might be struck. There is a discussion of key implementation requirements, particularly the role of information, knowledge and communications and of conflict resolution mechanisms. Chapter 6 on <u>local level governance</u> looks at the promising but vexed potential for improving outcomes through participatory and collective management approaches.

4.1 The Influence of Context in Determining Groundwater Policy and Governance Systems

The Key Characteristics of Groundwater that Affect Policy and Governance
It is hard to impose a system of governance on groundwater because of its very nature as well as a number of inherent or acquired characteristics described below.

- <u>*De facto* appropriation</u>: Although groundwater is a common pool resource akin to surface water, its unseen characteristic combined with well technology has allowed individuals to establish *de facto* water rights to what is under their land.
- <u>An individualized resource</u>: Although, in principle, groundwater could be a common resource, in practice it is generally abstracted by individual well owners from under their own land. This individual character frees the user from constraining governance or cooperation with neighbours.
- <u>Strong economic drivers</u>: In most situations, groundwater is free of charge, of excellent quality, and can be turned on and off like a tap.
- <u>No inherent incentives to sustainability</u>: Because each user is accessing a shared aquifer and because groundwater flows, particularly when rapid extraction is taking place, each user is in competition with neighbours in a “race to the bottom.”
- <u>Unseen</u>: Because the resource is underground, it is hard to quantify and equally hard to manage. Negative impacts may remain unseen for years and no physical limits are visible to the user or decision maker, both of whom can underestimate the problems and convince themselves that there is still time to act.

There are three implications of these constraining characteristics for the formulation of policy and governance options for groundwater. The first implication is that options for groundwater policy and governance <u>need to reflect the challenging characteristics of the resource</u>. A second implication is that governance systems also need to be <u>proportional to outcomes</u> that can reasonably be anticipated. The final implication that might be drawn from this rather daunting list of constraints is threefold: that <u>gaining information is vital, that</u> a <u>learning approach is essential</u>, and that countries should <u>expect only moderate outcomes</u>.

Groundwater Within Overall Water Resources
Groundwater has to be seen in the context of the country's overall water resources.

The importance of groundwater in total water resources either locally or nationally will influence the need for development of policy and governance. For example, in cases such as that of India, where groundwater is a very important component of total water resources and is the main resource for a highly important agricultural sector, operation of a workable governance system is a top priority. Again, since groundwater resources and uses are often poorly monitored, the true importance of groundwater in a nation's water balance can be underestimated.

Groundwater has to be considered as part of the hydrological cycle and it may play a variety of roles. For example:
- The main resource may be a fossil reserve, which means that exploitation is akin to mining, and policy needs to determine the rhythm at which it is exploited.
- There may only be shallow alluvial aquifers which are best exploited to the full, consistent with environmental needs.
- There may be strong connectivity between the groundwater table and upstream and downstream flows.
- There may be a series of aquifers, one on top of the other, where different uses and users may have access.

Clearly, in all cases, groundwater policy has to be part of overall integrated water resource management policy, but the policies and governance mechanisms may vary considerably depending on whether there are inter-generational effects of current use (the case of fossil water), or current third-party effects or externalities (the case of aquifers with sizable connectivity, the case where wetlands or oasis ecosystems depend on groundwater, and so on).

Therefore, in assessing options for groundwater policy and governance, there is a need to evaluate how important groundwater is as a water resource and what is the role of groundwater in the overall cycle, and hence its role in integrated water resources management. Policy and governance arrangements need to be adapted to the realities of the situation and to the nature of the problems to be solved.

The Impact of Physical, Geographical or Socioeconomic Characteristics
Many physical, geographical or socioeconomic characteristics may affect the kind of governance system that would work best. Examples include:
- Groundwater in a rugged terrain, where visits are difficult, is unlikely to be regulated by outside controls.
- The costs of regulation could be prohibitive if wells are scattered over a wide area.
- Societies with strong traditions of local or tribal autonomy would resist attempts to impose top-down regulation.
- There may be a strong history of directive management, as in FSU countries, and this may make top-down approaches easier.
- Legacies of exclusion may make cooperation between local communities and the state difficult to implement (see Box 5).
- There may be generally low levels of respect for state institutions or the law, or resistance to change or lack of adaptive capacity (see Box 6).

The lesson is that governance structures need to reflect a realistic appraisal of the physical, geographical and socioeconomic realities.

The Importance of the History of the Development of Groundwater
Policies and governance systems have to reflect the state of development of the resource. In many situations, the "cat is already out of the bag" and returning to an optimal situation is impossible. As a result, governance systems must adapt to the extent to which groundwater is already developed (or over-developed). For example, in Tanzania where the resource is only 3 percent developed, it may be possible to implement a model licensing and regulatory system. In the Deccan Traps Basalt Aquifer in Andhra Pradesh, by contrast, where the resource is more than 100 percent developed and where there are over 1.7 million borewells, lower cost and less administratively burdensome approaches are essential.

Box 5. Historical Legacies and Participatory Approaches

Historical legacies have profound effects on shaping the way stakeholders engage in participatory management. Macro-level institutions are often the result of traditions going back generations and hence the practical scope for change in the short term may be limited. In South Africa, the legacy of apartheid militated against effective participation, with poor basic education, a history of dependency and a general lack of confidence in politics and policies strongly limiting the involvement of grassroots rural users and citizens (Wilson and Perret, 2010). For example, Levite *et al.* (2003) investigated the quality of participation in the development of the Olifants Catchment Management Agency and showed that meaningful participation of users is not only constrained by lack of information and education, but also by local tensions and by the lack of history of dialogue between users.

Box 6. Community Acceptance of Rules Imposed from Above

Community values may lead to lack of acceptance of new rules imposed from higher level institutions. For example, in Morocco, the implementation of demand management measures by the introduction of drilling permits and fees has led to sometimes violent conflict in the Souss-Massa area (Houdret, 2006). Similarly, in Spain, many farmers perceive high-level interventions as an attack on their rights to generate profit and are unwilling to change their water use practices (Closas, 2012). In many countries, the establishment of water user associations and cooperative societies often fails because of top-down implementation and subsequent lack of ownership (in addition to insufficient financial resources). In such cases, communities may require evidence of tangible benefits to assure their participation (Olson, 1971; Sreedevi *et al.*, 2004), particularly where adversarial relationships between government agencies and communities exist.

Adapting Governance to the Nature of the Main Problems

Governance systems should be designed to bring actual outcomes as far as possible in line with policy objectives. Those objectives may vary, depending on the nature of groundwater problems. For example:

- Where rampant depletion is the main problem, governance will focus on reducing abstractions.
- Where agriculture is using the lion's share of groundwater but adjacent cities desperately need water, governance mechanisms to facilitate water transfers from agriculture to municipal and industrial uses are needed.
- Where pollution of aquifers is a real problem, mechanisms will need to be devised to ensure protection from polluting sources.
- Where land use in recharge areas like watersheds is reducing recharge, mechanisms to ensure watershed management and protection are indicated.

The lesson is that governance is not "one size fits all" and systems need to be adapted to the key problems experienced or anticipated.

4.2 Groundwater Policy and Political Economy

Stated Policy and "Real Policy" on Groundwater

"Policy" is here loosely defined as *a nation setting objectives*. In the case of groundwater, stated policy would be context-specific, reflecting some of the considerations discussed in 4.1 above, but would have something to say about the three typical development objectives of sustainability, efficiency and equity:

- *Sustainability* in quantity and quality
- *Efficiency* in allocation within and between sectors to the highest societal value
- *Equity* by ensuring fair access and firm entitlements

In practice, however, there is usually a gap between stated policy and "real" policy, in that "real" policy is not what the country says but what it does. A good example is the case of unsustainable abstractions.

Unsustainable Extractions v. Sustainability Policies

Despite policies for sustainability, overdraft is often the norm rather than the exception. This could simply be due to lack of knowledge, but most commonly reflects a "real" policy to reap short-term economic benefits.
Almost all groundwater policy claims to target sustainability; that is, to ensure that over the medium or longer term abstractions equal recharge. However, continuous over-abstraction occurs in many locations, to the extent that it could be seen as the "real" policy. Why does this occur?

In practice unsustainable use of groundwater is quite common for a variety of reasons. It can be the result of ignorance or lack of knowledge about the dynamics of the groundwater system. Since groundwater is invisible there are no direct signs telling a population and its decision makers how critical the condition of the groundwater resources may be, unlike a river that is drying up or fish dying in the river to warn of pollution. Information on the critical status of groundwater resources may not be sufficient to trigger action.

In many cases, the unsustainable use of groundwater reflects a "real" policy. Users have many incentives to over-use (see section 4.1 above) and policy makers turn a blind eye. Faced with urgent needs and limited budgets, decision makers will acquiesce in the use of groundwater above sustainable levels to satisfy water demand (for irrigation, urban or rural water supply and industrial uses), even if there are signs that the groundwater use is beyond levels of long-term sustainability. The case of the Indian energy/groundwater nexus is perhaps the best example (Box 7).

Box 7. The Nexus Between Energy and Groundwater in India

In India, politicians and the agricultural lobby fight against bans on groundwater development and promote cheap energy.

India is the most well-known example of a difficult political economy for groundwater management. Shah (2010) explains it this way: "[The] Central Groundwater Board categorizes areas (blocks of around 100 villages) according to the state of their groundwater development from white (under-developed) to dark (critical and over-exploited blocks). In theory, new tubewells are banned in the latter areas; yet, come an election, and politicians relax the ban,"

There is also a dimension of equity between the better-off and the poorer farmers that heightens existing tensions. Agricultural development banks like NABARD do not finance new tubewells in over-exploited blocks, so the poorer farmers cannot access credit for that purpose. Better-off farmers, by contrast, can use their own funds to deepen wells.
Similarly, agricultural power pricing and minimum support prices for crops have emerged as powerful drivers of groundwater use, but reforming the provision of free or cheap power is a politically sensitive question. In some states, such as West Bengal, the government installed meters on all electrified tubewells, introduced remote meter readers, imposed a time-of-the-day power tariff, and cut farm power subsidies. The government was able to do this because the capacity of electric tubewell owners to put up political opposition was limited since less than 10 percent of the shallow tubewells are electrified. This solution cannot be applied in Gujarat state where 800,000 out of 1.1 million irrigation tubewells are electrified and groundwater irrigators organize quickly and easily around power supply and pricing issues (Shah, 2010).

Convincing decision makers to adopt a strategy moving towards sustainable groundwater use has proven to be very difficult and interested groups exert pressure to allow over-drafting.

Lack of support for sustainable use is partly due to lack of political awareness, perhaps stemming from failures to provide adequate information on the groundwater situation to decision makers. However, even where knowledge is available, it is not necessarily turned into political action. The tendency of policy makers is to address short-term needs first and look into poorly known long-term threats later.

Politicians are under pressure from stakeholders and interest groups not to take decisions that have an adverse impact on their immediate needs or gains. For example, powerful lobbies are now involved in defending the interests of groundwater farmers in the United States, India, Morocco, Saudi Arabia, Spain and elsewhere.

Neglect of Groundwater Issues by Policy Makers

Groundwater reform is politically difficult and can become a low priority.

A second reason for the gap between stated policy and "real" policy is that policy makers tend to see more pain than gain in dealing with groundwater issues. The problems of groundwater are complex and solutions are rarely clear-cut. In the expansion phase of groundwater development, policy makers may find considerable political benefits in promoting development for their constituencies, but once groundwater is well developed and problems start to emerge, downside costs predominate. The agenda becomes one of regulation, demand management, even water charges, none of which hold political advantage. Promoting such a reform agenda would require an expenditure of political capital that few policy makers are prepared to make.

Decision makers find it difficult to take unpopular decisions with immediate socioeconomic impacts to address long-term threats that are building slowly.

As with other natural resource issues, tackling groundwater reform requires a long view and might need sustained commitment for several decades. Few politicians have such vision or stamina. Ironically, it is in hereditary monarchies like Oman, Jordan and Morocco that rulers have been prepared to take such a long view.

One implication is the importance of looking not just at decision makers but also at the interests of their constituencies. For example, reforms that will have significant impacts on agriculture must first be sold to farmers. The common arguments that attribute failure to implement a policy reform agenda solely to a lack of political will ignore the essential requirement of building constituencies of popular support.

Attitudes regarding groundwater are in stark contrast to surface water projects, and this affects public spending allocations.

Politicians tend to favour highly visible infrastructure projects that can bring political gain. This may lead to neglect of investment and recurrent budget allocations for more effective and efficient investments. For example, in relation to groundwater, Gonzalez de Asis *et al.* (2009) highlight that large dam projects may be favoured over more efficient groundwater developments.

The Way Forward: Towards Improved Groundwater Policy

<u>Do the Political Economy Analysis</u>

Understanding the political economy of groundwater is key to any effort to improve groundwater governance.

Political economy questions involve power relations that are difficult to appraise, but understanding them is key to improving outcomes. There is now much evidence to show that the success of development initiatives depends as much on having the right confluence of political factors or avoiding major political risks as it does on having the right technical design (GAC, 2011; Williams *et al*., 2007; Fritz *et al.*, 2009 in Schmidt *et al.*, 2012).

Tools have been developed to analyze and assess the political economy.

Political economy *analysis* is concerned with the interaction of political and economic processes in a society; that is, the distribution of power and wealth between different groups and individuals, and the processes that create, sustain and transform these relationships over time.[22] More specifically, a more thorough *assessment* of the political economy looks systematically at the institutional structures and the formal and informal rules of the game that surround and interact with them (GAC, Mar 2011). Political economy assessments may comprise a variety of analytical tools such as stakeholder analysis, analysis of winners and losers, institutional and governance analysis, and risk assessments (World Bank, 2009a) (Box 8).

<u>Provide Decision Makers with the Information They Need to Take Action</u>

Sharing of information both with decision makers and with all stakeholders (including the general public) is likely to improve the quality of decisions.

[22] See Collinson, S., nd http://www.oecd.org/document/8/0,3746,en_2649_34565_37957768_1_1_1_1,00.html

Raising the level of awareness among politicians, decision makers and stakeholders (including those from other sectors) about the real threats to groundwater resources is the first step in improving groundwater policy and governance. Transparent provision of appropriate information will equip politicians to take decisions in the light of the facts, and also allow stakeholders and the general public to influence those decisions. Box 9 illustrates how threats of groundwater depletion were convincingly presented to policy makers in one country.

Box 8. Identification of Political Risk and Stakeholder Mapping

In order to recognize the political risks faced by a proposed project, there needs to be an assessment of actors (such as politicians or interest groups), along with their attitudes, motives and power to support or oppose. Having identified actors that are likely to oppose a project, it is helpful to assess their channels of influence to gauge the threat they may pose. Finally, it is important to consider the actual impacts political risks could have at different stages of a project cycle if they were to materialize (Schmidt *et al*., 2012).

In the specific case of groundwater governance, part of this approach may involve stakeholder mapping–a process of particular relevance given the complexity and political nature of the groundwater sub-sector. Mapping helps to determine the positions, levels of influence and power of different actors, their inter-relationships, and the channels through which influence occurs.

Sources: Schmidt *et al.,* 2012; World Bank, 2012b.

One first step is to convince decision makers to put aside required budgets for acquiring information.

This could start with the allocation of budgets for groundwater resources assessment and monitoring, to gather the critical knowledge needed on the water resources. Groundwater systems are generally more complex than surface water bodies and information is more costly to obtain. The reality is that in many countries the amount of systematic time-series information on groundwater resources is scarce (IGRAC 2004). Showing the value of groundwater to the nation's economy and the cost of depletion may help to make the point that paying for groundwater knowledge is worth the investment.

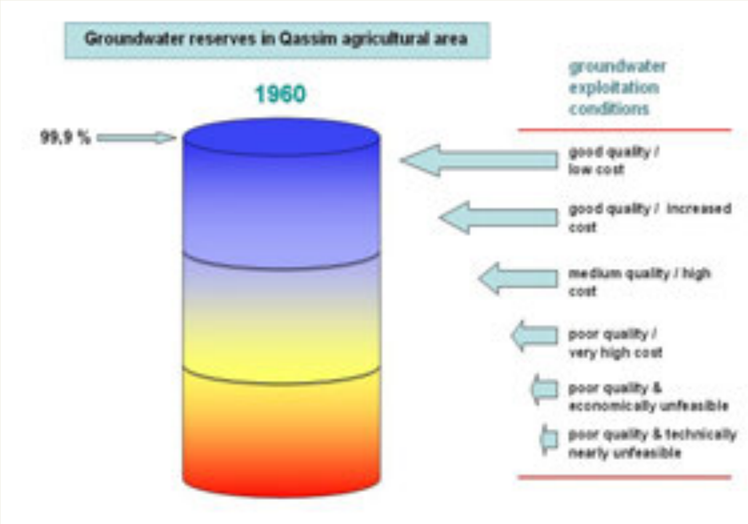
The groundwater community needs to adapt the message to align it with the interests of stakeholders by showing the economic impacts of decisions.

Providing decision makers with up-to-date information on the condition of groundwater resources and their expected life is critical, but in many cases it is not sufficient to trigger much needed action. The importance of groundwater to the national economy may go unnoticed and the contribution of groundwater to the nation's food security, water supply or economic development may need to be made visible. To raise awareness there is a need to demonstrate the real value of groundwater in the economy to convince decision makers that the cost of inaction largely exceeds the cost of action.

This kind of analysis can be complex and it needs to be disseminated in a form that is easily understood by politicians and the public

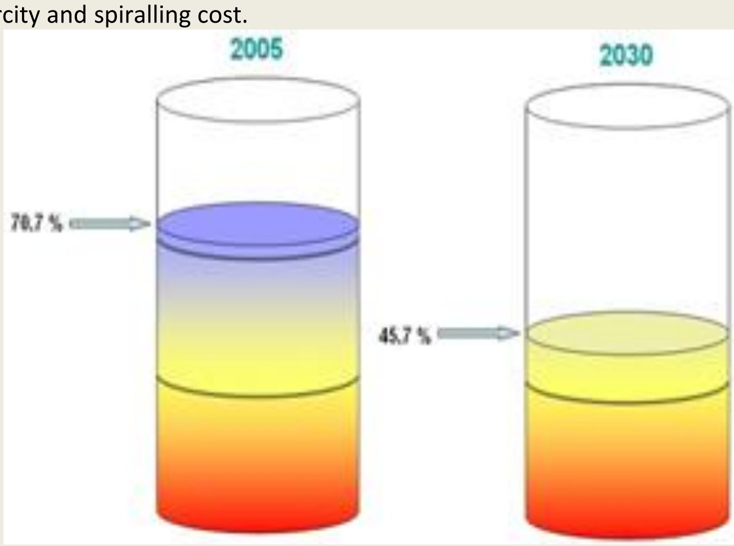
This is easier said than done. Groundwater has multiple users and multiple functions, often with cascading effects on other sectors. As a result, decisions (or the lack thereof) about groundwater have an impact on many sectors of the economy. There is a need to develop adequate tools and methodologies for analysing the groundwater economy to show the value of groundwater and quantify the risk of inaction. These tools need to consider the physical relationships and constraints of groundwater and understand its role with regard to surface water and other environmental entities and functions. Within this physically-based framework economic functions need to be modelled to allow for objective and relevant economic analysis of scenarios and quantifying the short- and long-term impacts on budgets and on individual stakeholder groups.

Box 9. Exploitable... But at What Cost?



In the early 1960s, before the introduction of tubewells and industrial agriculture to the area, groundwater in the Qassim aquifers was in natural equilibrium. At the start of groundwater exploitation, fresh water (blue colour) was easy to find and available at limited cost because of the shallow depth and short transportation distances from the point of use. As water mining continued, the level of water in the aquifers dropped, with an ever expanding cone of depression, and the quality of remaining water deteriorated. Some aquifers began to show increased levels of natural radioactive isotopes as a result of this intensive exploitation.

Over time, the freshest and most easily accessible water is depleted (see drums for 2005 and 2030, compared to 1960), leaving behind marginal quality water at much greater depth, affecting far wider areas as the cone of depression further expands. Thus, although the potentially exploitable amount of water in the aquifers is still significant in terms of quantity (about 45 percent by 2030), in part of the region the groundwater will have been depleted and in the remaining areas the poor quality and the much greater depth to the water table mean that producing potable quality water from the same well will now cost very much more. Deeper wells, larger capacity pumps and additional treatment facilities will be needed to make the water potable. The combination of deteriorating water quality, increasing depth and growing distance from centres of use creates a "perfect storm" of extreme water scarcity and spiralling cost.



Once the analysis is done, it needs to be formatted and disseminated in a way that is both understandable by the layman and conducive to informed debate and good decisions.

Figure 4 illustrates a cogent presentation of the economic impacts of groundwater over-abstraction in Saudi Arabia.

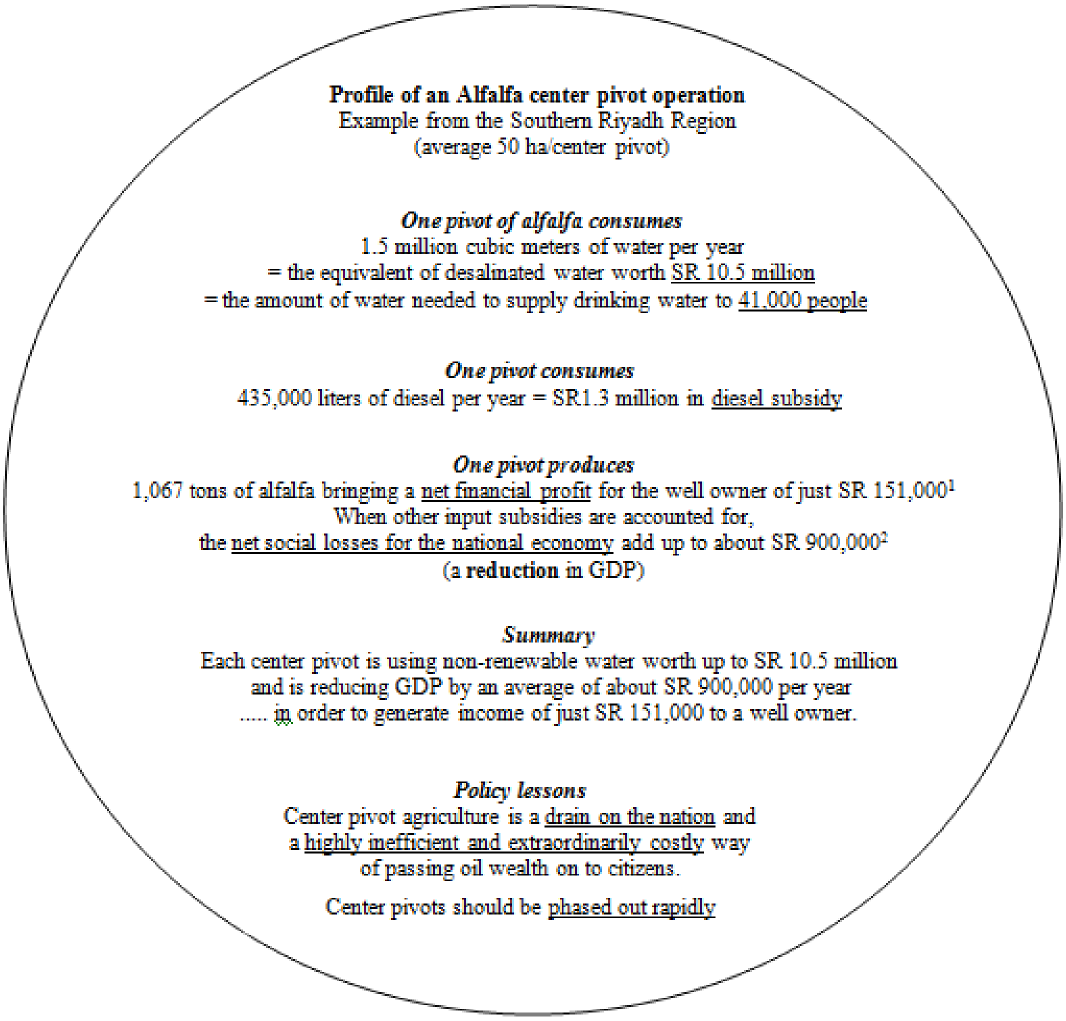


Figure 4. Economic Arguments for Groundwater Governance and Conservation in Saudi Arabia.
Explanation: Example of using a pivot-shaped presentation to draw the attention of decision makers to economic arguments for groundwater governance and conservation. A pivot is a large round field irrigated by a rotating sprinkler system. There are thousands of pivots in Saudi Arabia utilizing mainly fossil groundwater (source: World Bank, 2012a).
Notes:
[1] *Net profit excluding land rent;*
[2] *Net social losses are calculated on the assumptions that 60% of pivots use diesel pumps and 40% use electricity*

Ensure Accountability
Good groundwater governance requires both political and social accountability.

Given the importance of strategic and local level actions for good groundwater governance, both political and social accountability play equally essential roles.

Political accountability is when the state makes itself accountable to the public. It is supply-driven and relates to the organization of government systems and how they respond to community demands (Cotlear, 2009). Political accountability needs to precede, or at least match, social accountability by providing vision and the resources/incentives necessary to facilitate adequate community governance.

Conversely, social accountability[23] is demand-driven and refers to the ability of citizens, service users, project beneficiaries, communities, and civil society organizations to call for greater accountability and responsiveness from public officials and service providers (WB, nd). Social accountability mechanisms (see Box 10 and Annex 6) can be initiated from a variety of sources, but frequently operate from the bottom up. They are particularly relevant to groundwater governance where community engagement plays a critical role in resource management.

Box 10. Social Accountability Tools

There is a large suite of social accountability tools, chiefly centred on the promotion of principles including community ownership, subsidiarity, transparency and accountability (see Annex 6). Examples of the variety of tools available include community reporting and juries, grievance redress mechanisms, social auditing, public expenditure tracking systems from central to local government and community, and many others.

Many of the tools build citizen and civil capacities and awareness through the dissemination of information and promote dialogue between stakeholders. In addition, they may promote analytical and advocacy work and facilitate community engagement in collaborative formulation, decision-making and monitoring activities. Engaged and informed communities can better hold governments accountable for budgeting and service provision and also help to promote locally identified and coordinated actions. Iterative community management may be promoted by incorporating feedback mechanisms (soliciting perceptions on quality, efficiency and transparency), and deliberative participatory instruments may supplement conventional democratic processes. The structure of mechanisms may involve the formation of cooperatives and full community management and ownership of services. Monitoring may involve independent, third-party citizen, and community and civil society organizations.

Hence, social accountability tools may help promote more transparent and accountable management at both the local level (i.e. for collective management arrangements) and between the local level and various higher levels of government.

Sources: GAC, 2011; WBI, 2009a

Strengthen the Political Economy Debate

Recent analysis and experience have highlighted how reform programs can be helped forward by a proactive strategy to turn political economy constraints into advantages. Although this enters into the delicate arena of power relations and politics, developing and supporting such programs is entirely in line with the focus on the key role of political economy in getting the right policies and governance into place. Box 11 gives an example of how a strategy to promote reform and overcome political economy hurdles might be designed.

[23] Sometimes referred to as Demand For Good Governance (WB, nd).

Box 11. Design of Strategy to Overcome Political Economy Constraints and Reform Groundwater Policy and Governance

Ways and entry points to push forward a change agenda might include:

- Carrying out intelligent analysis and design: as part of the design of groundwater reform programs, analyse the internal political context and power balance of different stakeholder interests and influences as well as institutional structures and processes. "Implementing policy change that threatens deeply-rooted practices and interests requires a good understanding of the power relations that sustain them" (Zeitoun, 2009). Analyse the incentive structure and ensure that incentives can be rebalanced to influence positive change. At the local level, understand the adaptive capacity that exists in every community, and build on it as the key to predicting and promoting change. Balance access and comprehension of information and knowledge about resources and rights in order to empower stakeholders to participate and increase legitimacy and equity.
- Taking a strategic approach to engagement: design a targeted engagement strategy for identifying and dealing with opponents of reform. Such a strategy would include policy analysis, PR campaigns, public education, establishing dialogue platforms, and so forth. It will be very important to demonstrate and publicize facts on the ground. While discussions of ideas will influence ministries and academics, evidence of success or changes in incentives are needed to change things on the ground.
- Building constituencies. Reform requires a constituency, and time is needed to develop one. The role of leaders, catalysts and educators is important. Donors can contribute materially in this role. Think long-term, invest in a learning process. Develop a long-term strategy, and ensure that principal partners in government, civil society and among donors retain the stamina needed. Also, be ready to capitalize on "decisive moments."
- Developing capacity. Build up the water ministry and other relevant public agencies, with particular emphasis on improving the accountability of government and public agencies and on improving perceptions of their legitimacy among constituents. Empower water user associations and other weaker interest groups, enhancing their negotiating capacity, etc.
- Keeping to policy objectives. Ensure that the fundamental policy goals are always in mind: social equity in terms of fair distribution of benefits, economic efficiency, and environmental sustainability. Ensure a pro-poor bias to all measures, considering for example: (i) increasing the role of women and other vulnerable groups; (ii) poor-sensitive pricing; and (iii) emphasis on participation, accountability, transparency.

Source: Ward (2009); Zeitoun (2009).

5. Governance at the Strategic Level

The analytical framework presented in Chapter 2 distinguished three levels of governance functions: the policy level, the strategic level, and the local level. Following the discussion of the policy level in Chapter 4, the present chapter looks in some detail at the components of strategic level governance:

- The integrated water resource management (IWRM) planning function (5.1)
- Three governance approaches: (i) laws, rights and regulations; (ii) the incentive framework; and (iii) the framework for subsidiarity (5.2)
- The key governance function of information and knowledge and of communications with stakeholders (5.3)
- Mechanisms for conflict resolution (5.4)

The discussion of each comment looks in turn at: (i) the nature of the function; (ii) the typical impediments to good performance; and (iii) options for removing or alleviating the impediments.

5.1 IWRM and Cross-Sectoral Harmonization

The Principles and Practice of Integrated Water Resources Management
For the last two decades, water resources management around the world has been aligned on a set of best practices known collectively as integrated water resources management or IWRM.

Although IWRM practices are many and various (there are over fifty "tools" in the Global Water Partnership's "Toolbox for IWRM"), they can be summarized under five principal measures: (i) participation of all stakeholders in accountable governance structures and mechanisms; (ii) separation of water allocation authority from water users; (iii) decentralization and management at the lowest level; (iv) an incentive structure reflecting the value of scarce water; and (v) integrated inter-sectoral management at the basin level. Box 12 gives a synopsis of IWRM best practices.

Most countries have set up specialized water resource management agencies, sometimes as authorities, sometimes as ministries. In some countries (India, for example, see Chapter 3) specialized agencies have been established specifically for groundwater. The basin management approach has been reflected in the establishment of basin management agencies in a number of countries (Morocco, for example, Chapter 3). These agencies are typically responsible for devising and implementing water policies and strategies, for water resources planning, for information, and for regulation.

Although in principle IWRM should consider groundwater adequately, in practice it is often the poor relation, with negative consequences for agencies and for resource management.

One strength of the IWRM approach is that all water sources are considered in the planning framework in an integrated way, so that the role and special characteristics of groundwater are, in principle, fully recognized. However, a risk of this type of approach is that groundwater may not receive the same attention as surface water because of the constraints identified in Chapter 4 (4.1). As a result, groundwater may not be adequately considered in IWRM planning, and this can have very negative consequence for subsequent implementation. In addition to the risk in water management decisions stemming from lack of proper understanding of hydrological relationships, there are often negative consequences for water management organizations, including lack of budget and staff (see Chapter 3).

Impediments to Integrated Management Approaches to Groundwater

<u>Competing Interests and Lack of Cross-Sectoral Cooperation</u>
Agricultural policy and strategy are the dominant drivers of groundwater use in most countries, and alignment between water resources strategy and the strategy for agriculture is very challenging.

The agriculture sector is the main user of groundwater in many countries. Understanding the incentives of this sector is key to achieving sustainable groundwater management. The main issue is that, as agriculture develops, more farmers depend on groundwater for their livelihood, and reforms become socially and politically challenging. The case of the energy/groundwater nexus in India was discussed in Chapter 4 (Box 7). In Morocco, a combination of profit-driven lobbying by farmers and the government's concern for protecting a key economic sector while managing groundwater for sustainability have led to a step-by-step strategy based on the notion of "more income for less drop" (Box 13). However, it is not yet clear whether this actually will result in reduced overdraft and ultimate sustainability of the groundwater resource.

Box 12. IWRM - Global Best Practices in Integrated Water Resource Management

Global best practices in water management have emerged over the last twenty years, and most water laws and national water strategies are aligned with these best practices, which are typically grouped under the title " integrated water resource management" (IWRM). Essentially, best practice IWRM sets three goals for good water management, and four principles for forming policies and actions.

Three goals for good water management. The three goals of good water management are (i) social equity, (ii) economic efficiency, and (iii) environmental sustainability.

Under (i) social equity:

- Water services are available for all
- Existing water uses are respected
- Benefits of development are shared equitably, with care for the poorest

Under (ii) economic efficiency:

- Income per drop is maximized
- Water is available for its highest value economic use

Under (iii) environmental sustainability:

- The water resource and the broader environment are not harmed
- The needs of future generations are taken into account

The Dublin statement on water and sustainable development for action at local, national international levels. The four principles adopted by the UN Dublin Conference in 1991 for forming IWRM policies and actions are:

(i) *Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment*. Effective management of water resources demands a holistic approach, linking social, economic and environmental components across whole catchment areas and groundwater aquifers.

(ii) *Water development and management should be based on a participatory approach*, involving users, planners and policy-makers at all levels. This involves raising awareness of the importance of water and promotes decision-making at the lowest appropriate level with full public consultation.

(iii) *Women play a central part in the provision, management and safeguarding of water*. Acceptance and implementation of this principle requires positive policies to address women-specific needs and to equip and empower women to participate at all levels; and

(iv) *Water has an economic value in all its competing uses and should be recognized as an economic good*. It is vital to recognize the basic right of all human beings to have access to clean water and sanitation at an affordable price. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

Groundwater is used as an input to several sectors and, as a result, is affected by several sectoral strategies. Yet, there often are no mechanisms for alignment of strategies in pursuit of an integrated approach to water resources management.

The case study reports present many examples of sectors with competing interests, such as agriculture, mining, and land planning or conflicting claims regarding the supply of drinking water, water for irrigation, industrial supply, and minimum flows for sustaining ecosystems.

Box 13. Water Efficiency Subsidies in Morocco

In Morocco, subsidies are given to promote water use efficiency, but it is not clear that they produce the expected conservation outcome.

Morocco's agriculture sector has been the main driver of groundwater development, and policies that restrict groundwater pumping are now difficult to implement. The agri-food sector is a pillar of the Moroccan economy. It represents 15 percent of Morocco's GDP and 23 percent of the country's exports (World Bank, 2011d).

In particular, the Souss Massa aquifer is used to irrigate crops for high-value export markets and it is one of the most over-abstracted aquifers in the country. The case study report shows that there is a lack of sustained support from elected councils and local authorities for the actions proposed by agencies to enforce groundwater provisions such as control of drilling activities or groundwater abstractions, and groundwater permit requirements.

The "water saving" action most easily accepted in irrigated areas is the conversion of gravity irrigation into drip irrigation systems, which often benefits the farmers by increasing yield and decreasing pumping cost. However, it is uncertain how much water the introduction of drip irrigation will save. In other countries in similar situations, water saving techniques employed in the absence of regulation have led to an *increase* in water abstractions (Foster *et al*., 2009). Things may be changing with the new management plan for groundwater in the Souss-Chtouka aquifer, which includes a reduction in areas irrigated by groundwater, at a rate of 1 percent per year.

Development and implementation of management strategies often remain a problem because of poor cooperation between sectoral ministries, poor cooperation across administrative boundaries (see section 4.6), and also the protection of vested interests not only by states but also by important individuals in government, industry and even in the science fraternity. Thus, the process of formulating groundwater strategies should involve not only representatives of the different sectors that depend directly on groundwater (such as agriculture or industry), but also sectors that indirectly affect groundwater (such as urban development, land planning, mining) as well as the whole water sector. A major challenge to groundwater governance is cross-sectoral cooperation. If successful, cooperation between policy fields and sectors provides tremendous opportunities in terms of cost efficiency.

<u>Demarcation of Management Areas</u>
Problems may also arise from the mismatch between hydrological and administrative boundaries.

The geographical mismatch between hydrological and administrative boundaries has often been mentioned as an administrative gap in water governance (OECD, 2011). It is a challenge relevant to both surface and groundwater resources and requires coordination between the authorities. Administrative boundaries are determined by political, geographical and historical factors that may have nothing to do with natural hydrological boundaries (which commonly intersect local, intra-national, or international demarcations). If this mismatch is recognized by the responsible authorities, coordination with all related sectors may contribute to better integrated water management. This discrepancy between hydrological and administrative boundaries is most problematic in cases of transboundary aquifers (described in Box 22 and Box 27). Such barriers may best be overcome via strategic IWRM at basin scales.

<u>Constraints to Factoring Groundwater into Integrated Water Resources Management</u>
Water management agencies often give low priority to groundwater compared to surface water.

The tendency of decision makers to favour visible surface water plans and investments (Chapter 4) is paralleled by similar preferences among planners and engineers. The integration of surface and groundwater budgets can potentially exacerbate this issue. When budget shortfalls occur, it is generally easier to postpone or cancel the less visible groundwater-related activities than the more visible surface water activities. In India, water supply planning and investment at municipal or state levels is almost entirely restricted to large capital investments for the development of new surface water sources (World Bank, 2010b).
*When groundwater **is** considered, the focus tends to be on development rather than conservation.*

It is easier to obtain financing for water sector infrastructure than for the software needed for groundwater (such as research, policy-making, monitoring, environmental and pollution control, training, and public awareness). Shah (2010) notes that Indian farmers, NGOs and governments have been far more enthusiastic about augmenting the supply of groundwater resources than managing demand and reducing overdraft. In an analysis of water governance in Kenya, Rampa (2011) observed: "There are strong incentives, including for the government, parastatals and donors, for achieving immediate results on access to water services, while conservation and long-term sustainability of the resource does not seem to be an immediate priority." This problem is exemplified by the comparison between the Water Services Regulatory Board (which receives substantial support and is under pressure to improve access to services) and the Water Resources Management Authority (which receives little government attention).

Integrated water resources management can even be detrimental to groundwater if adequate expertise is lacking. In South Africa, the water sector has been restructured, with groundwater being integrated into all other water management functions, such as planning, information management, and resource protection. The former Directorate of Geohydrology was dissolved and hydrogeologists were redeployed to a number of directorates and integrated with surface water sections. While the purpose of this restructuring was to ensure integrated water resource management, it left the new Department of Water Affairs without a central coordinating point or "champion" for groundwater. The lack of a central focus or champion results in inadequate coordination with and support for regional offices and municipalities. The Indian state of Andhra Pradesh is considering establishing five river basin organizations to take over water resources management functions in the longer term. While there may be potential benefits associated with such a proposal, groundwater-specific challenges identified by the Bank (Apr 2009) include: (i) local-scale groundwater issues not receiving the level of attention they deserve; and (ii) breaking up the critical mass of experienced groundwater professionals in the state government.

Options for Overcoming the Impediments

Aligning Interests and Harmonizing Sector Polices

Correcting the mismatch or conflict among sectoral policies is one of the biggest challenges for groundwater governance.

Typically, the political gain and economic incentives weigh in heavily on the side of the water using sectors, particularly the interests of agriculture and municipal and industrial supply. Within the water sector, the scales are heavily weighted in favour of surface water investment and related management. What governance mechanism can ensure that sectoral policies and integrated water resources management planning promote good groundwater management?

Countries have set up a range of inter-sectoral coordination mechanisms, and there are excellent examples of multi-level governance concerning groundwater.

A variety of approaches to promote inter-sectoral coordination have been developed, including: (i) creating a specialized ministry or water resource management agency with the mandate of coordinating all water-related policy; (ii) confiding a coordination role to a neutral ministry, typically the planning ministry, to reconcile the interests of the water resource managers with the water using sectors; and (iii) creating a high level governance body such as a national water council (such as the water and climate change council in Morocco, or the recently-created National Water Board in Tanzania). Institutional analysts have also proposed multi-level governance as a mechanism to facilitate cross-sectoral harmonization as well as vertical linkages between the centre and the local level. China has implemented these mechanisms to improve water and environmental management, including groundwater, in the Hai basin area (Box 14).

Box 14. Multi-level Governance of Groundwater in the Hai Basin

The groundwater underlying the North China Plain, within the Hai River basin, is used intensively for irrigated agriculture. Affected aquifers are shallow, unconfined and deeper, confined aquifers. Some areas have recorded an over 40 m drop in the groundwater level, which has increased the risk of salinization, especially along the Bohai coastline.

The objective of the World Bank-financed Hai Basin Integrated Water and Environment Management Project (2004-2011) was to serve as a catalyst for an integrated approach to water resource management and pollution control in the Hai Basin in order to improve the Bohai Sea environment. Based on previous Bank project experience and sector work, the project was focused on new and innovative approaches, many of which concentrated on improving governance.

1. Introduction of the new concept of real water savings whose aim was a reduction in consumptive use or evapotranspiration (ET) rather than just increases in irrigation efficiency (which normally leads to increases in consumptive use of water through increased effective irrigation areas). Experience in China had shown that focusing on improvements to physical infrastructure alone might increase irrigation efficiency, but it could also reduce groundwater recharge by increasing the proportion of rainfall or irrigation water consumed by crops through ET. This reduced availability of water for other users and the environment. Only a reduction in actual consumption of water represents a genuine saving of the resource to the hydrological system. The project introduced ET quotas or targets, which were based on a combination of actual ET values measured with remote sensing technology and models of surface water and groundwater systems.

2. Introduction of institutional mechanisms for cooperation among government departments in different sectors rather than the traditional sectoral line management and top-down (command and control) direction. This integrated institutional management comprised horizontal (cross-sectoral) cooperation between ministries, and their national, provincial and county equivalent agencies. The integrated management included establishment of horizontal and vertical project coordinating mechanisms, signing of data-sharing agreements, establishment of a joint decision-making conference system at the basin level, and interagency decision-making committees at the county level, and a suite of strategic policy studies and demonstration projects.

3. Introduction of a Basin-wide Knowledge Management (KM) System (including application of remote sensing ET measuring technology) located at the Hai Basin Commission and local governments. This included decentralized knowledge hubs at lower project levels. The system made it technically possible to share and allocate data at both basin and county levels by local governments and water use sectors within the basin. The key is that a quantitative linkage has been established of the monitoring indicators (e.g. target ET and target pollution discharges) between the basin-level and field-level, which greatly facilitated integrated river basin management.

4. Development and implementation of sub-basin and county-level Integrated Water and Environmental Plans (IWEMPs) to return surface and groundwater use and pollution discharge to sustainable levels consistent with the project's goals, ET quotas or targets, and water quality targets for water function zones.

5. Participation of the key stakeholders (the farmers) was achieved during project implementation by means of the establishment of Water Users Associations (WUAs) and by providing Community Driven Development (CDD) investments so that farmers' incomes increased considerably while consumptive use of water was reduced. The intention and the result of the CDD/WUA approach was to give farmers' incentives to participate in the whole process of the project design, implementation, operation and management. The communities made decisions on their own choices on the ways to increase their incomes and on how they were going to do water management.

Source World Bank 2011 (Implementation and Completion Report).

Groundwater needs to be adequately factored into IWRM planning.

Where integrated water resources management planning has been adopted, whether at the level of national master plans or at the local river basin level, specific dedicated human and financial resources should be devoted to groundwater. Some activities, of course, are common between groundwater and surface water, so creation of entrenched "empires" needs to be avoided. Cross-fertilization is also useful. For example, groundwater management can benefit from the experiences in surface water with regard to participatory approaches and collective choice arrangements, which are much more developed for surface water management.

Nonetheless, groundwater requires specialized capacity in term of knowledge and resource monitoring and additional efforts for information and communication compared to surface water (see Box 15). If river basin organizations are in place, groundwater should have its own space with separate responsibilities and budget to reflect its specificity. In some countries, surface water and groundwater are managed by different institutions. In India, for example, there are specialized national agencies for groundwater (see Chapter 3), and coordinating agencies for all groundwater related activities at state level.

Box 15. IWRM in Africa

In many African systems, river basins are the unit of choice for IWRM planning, with a hierarchy of governance organizations and institutions and with groundwater factored in.

Of 40 countries surveyed in the AMCOW report of 2012, 60 percent are implementing integrated water resources management at the river basin level, which is a significant increase from only a few years ago. The report recommended strengthening institutional frameworks to support and promote the establishment of effective governance and institutional frameworks for water resources, including groundwater, based on IWRM. Within countries, this could take the form of national committees or councils at the national level, of basin committees or agencies at the basin level, and of local water committees through institutional capacity development and peer-to-peer sharing of experience at the local level.

Source: AMCOW, 2012.

Proactive conjunctive management to resolve scarcity and quality constraints should be encouraged where it can make the difference.

Conjunctive management (that is, managing different parts of the land and water resource continuum jointly to improve outcomes) has several implications for groundwater. For example, the use of aquifers for managed storage of surplus surface water has broad application, ranging from small scale water supply and irrigation schemes to municipal supply where some form of aquifer-storage-recovery is possible. Confined aquifers can also be used for managed recharge with treated wastewater. In addition, the regulation of recharge through land management also offers scope to improve groundwater quality and quantity.

However, dealing with the third party aspects of protection and recharge is difficult.

For example, persuading individuals to reduce chemical inputs on land or change land management and waste disposal practices is harder than persuading them to change abstractions or water use since it is difficult to build in incentives to change (there would be no direct benefit to them if they are not drawing water from the aquifer). This is a very common challenge in watershed management projects, for example. The implications are twofold: (i) land management in the recharge area is an important part of aquifer management, and needs to be included in planning; and (ii) sustainable incentives need to be built in to interventions. Sometimes these can take the form of win-win investments, such as the planting of fruit trees to stabilize the upper watershed, which also produce an income for the farmer. In other cases, payments for environmental services (PES) may have to be considered.

5.2 Developing and Applying Governance Approaches

5.2.1 Defining a Governance Approach

The analytical framework in Chapter 2 distinguishes three governance approaches: (i) a rights and regulation approach; (ii) an incentives-led approach; and (iii) a subsidiarity approach.

A rights and regulation approach awards (or recognizes) legal water rights to users and then relies on a regulatory system to ensure that users are respecting the terms of the award. An incentives-based approach uses positive and negative incentives (typically incentives that affect the profitability of water use) to bring pumping behaviour at the well head into line with policy. A subsidiarity approach delegates responsibility for groundwater management to the local level, usually to stakeholder interest groups.

The importance of getting the right governance framework up-front is illustrated by the common disconnect between ambitious policy objectives and governance frameworks that are ill-adapted to the realities on the ground.

In all five of the study countries studied (see Chapter 3), public institutions in charge of regulating groundwater abstraction proved unable to implement the policy, especially the control of illegal drilling and groundwater over-abstraction. Morocco is certainly the most advanced country in terms of capacity but the river basin authorities are overloaded and understaffed and policing interventions remain inefficient.

The number of wells and users is a key determinant of whether an approach is feasible or not.

One lesson that could be drawn from the case studies is that if groundwater users comprise only a few water supply providers, regulation by government institutions may be feasible, but controlling groundwater abstraction from a large number of small-scale irrigators requires a level of staff, capacity and budgets that governments cannot afford. In these cases, incentives or subsidiarity approaches may be better suited.

In particular, regulatory systems that depend on the award or regulation of quantified water rights place a huge administrative burden on public agencies.

Issuing permits or groundwater use rights is also a massive administrative challenge. Considerable constraints were observed in all case study countries, and in other countries as well (Mexico and Peru have experienced similar difficulties) (see Box 18).

Taking the framework above, what are the characteristics of these different governance approaches, and when might they be adopted? These questions are answered in the following sections. Here it is important to note that the three approaches are not mutually exclusive. In reality, all governance systems will use a combination of approaches, and may use different ones for different geographical areas or segments of water users.

5.2.2 Rights and Regulatory Approaches

There have been many problems in defining, issuing and regulating quantitative groundwater rights.

A system of formal rights and regulations is very demanding in terms of knowledge, skills, manpower and financial resources. Such systems typically require:

- a legal framework that defines groundwater rights and the related regulatory system
- quantification of the water resource and a monitoring system that relates water abstractions to the groundwater balance and to related changes in the hydrological system
- a full well inventory and a record of existing and historic patterns of water use
- the issue of licenses to each right holder, spelling out the quantity that may be abstracted
- a system of measuring, recording and reporting on actual individual well abstractions (usually by metering)
- a compliance system, normally including inspection
- a legal framework and the police and judicial apparatus for dealing with infractions and for imposing sanctions
- a system for financing the relatively high costs of the regulatory regime

Recognition of existing rights is a common approach that is easiest to put into place when land ownership is clear, but if this still requires individual registration and regulation, it will scarcely reduce the administrative burden.

Patterns of groundwater rights had emerged in all the countries studied. These rights were usually based on the law of capture; that is, people acquired a right to the groundwater by drilling on their own land. These rights were locally recognized in Tanzania where, in some cases, traditional patterns of cooperation over water were established, such as local water rotations and user groups (Sokilea & van Koppen, 2004). Essentially, these groundwater rights are determined by land ownership. Thus, determining who owns the land is a shortcut for determining water rights. However, in many parts of the world, forms of communal tenure, leasehold or sharecropping blur this easy route to attribution.

Key in determining whether to go through the registration and regulation route is whether it is administratively feasible and affordable. Governments need to assess the feasibility and the transaction costs of implementing such a policy where many smallholders are concerned, and weigh the feasibility and the costs against the importance of the policy objective.

Systems based on top-down regulations have often run into problems of compliance (see Chapter 3). This is the case, for example, in South Africa where the level of compliance with existing regulations is relatively low. On the regulator's side, there was not enough capacity to monitor compliance or to follow up on infractions, and perhaps there also was a lack of political will to impose penalties. On the side of the well owner or water user, there was little or no acceptance of the regulatory regime and hence no incentive to comply.

Licensing systems essentially create entitlements, which may lead to contentious claims and even steeper administrative challenges.

A system of licenses confers entitlement and responsibility. The government may wish to manage the risks involved by, for example, issuing licenses only for a specific period, or establishing provisions for a progressive reduction of water abstractions, or limiting use to certain crops, or establishing requirements for downward variation in case of drought. However, from the government's perspective, these kinds of specific entitlements and responsibilities place enormous burdens on under-resourced departments. In addition, once entitlements are formally granted, they may be contested and result in legal proceedings (Van Koppen, 2010).

In addition, a rights and regulation system may run the risk of regularizing inequity or even increase it.

The process of establishing rights through an administrative and legal system requires a level of sophistication, time and access to information that few small farmers have. Given that the procedures are the same for larger or smaller users, the smaller users (who have fewer resources) are discriminated against. One solution might be to exempt small users from registration, either for equity or for efficiency reasons, but it is unclear how they can be protected against encroachment. In fact, there is always a risk that the more powerful will be able to appropriate an increasing share of *de facto* groundwater rights simply because they can drill more and deeper wells, and it is unlikely that a formal rights system would offer much protection in practice. Van Koppen (2010) shows that inequity *increased* with the increasing formalization of the water economy in Sub-Saharan Africa (Volta and Limpopo basins).

Options

In Yemen, for example, groundwater resources were captured by the better-off, and traditional governance set-ups could not cope with the challenges of the tubewell. The government's initial response was to introduce a rights and regulation regime, but experience over the years has shown that the administrative capacity, political will and stakeholder willingness to comply that are needed to make this a viable approach are lacking. Not surprisingly, results on the ground are hard to find (Box 16). *The lessons are twofold: first, persistence is vital; and second, governance approaches need to be adjusted to reflect experience.* In the case of Yemen, this is leading to a shift away from a rights and regulation approach to one more based on changing the incentive structure (by raising the price of diesel), and on subsidiarity and partnerships between local collective management organizations and decentralized public agencies.

Box 16. Reform in Yemen

The policy and legal systems reforms undertaken in Yemen are excellent on paper, but the negligible impacts to date show that top-down prescriptions may work better if they are matched with local collective management.

The political economy of water in Yemen had allowed groundwater resources to be captured by farmers, particularly the more powerful ones, who drilled wells and abstracted water at will. Traditional governance systems could not adapt to the changing situation and conflicts over increasingly exhausted resources grew. Both groundwater quality and quantity declined and costs increased.

In 1996, the government set up the National Water Resources Authority and charged it with issuing and regulating groundwater rights. This weak and under-resourced agency proved incapable of so daunting a task. As a result, wells proliferated and water tables continued to plummet. The government has amended its strategy, which now provides for the following:

- A decentralized management and stakeholder partnership approach, where the underlying hypothesis is that decentralization and promotion of community self-management will improve governance and help reduce resource capture and overdraft.
- Revision of the economic incentive structure for groundwater use, where the underlying hypothesis is that these measures will reduce incentives to over-pumping, enabling farmers to reduce water use while maintaining or even improving their incomes.

The new approach is having some success. Community organizations and user groups are coming together to stop illegal drilling, prohibit water transfers outside the community, protect drinking water sources, invest in recharge infrastructure, and improve irrigation and crop husbandry. Some success in getting "more income for fewer drops" is evident.

Sources: Ward *et al*., 2007.

When Might Rights and Regulatory Approaches Be Most Appropriate?
Registration through permits or licenses is an appropriate approach for larger users or the more formalized sectors, but other approaches may be a cheaper and more equitable solution where small-scale users are involved.

For example, in Saudi Arabia, groundwater abstraction for farming is basically unregulated, but the more formal industrial and oil sector users are the subject of an efficient licensing and monitoring system. It is proposed to extend this approach to larger company farms, which number only a few dozen but account for one quarter of total water use.

Experience shows that where large numbers of small users are involved, incentives and subsidiarity approaches may be the most indicated, particularly collective management approaches. In some cases, the rights and regulation approach may be applied only to larger users, and responsibility for management among small-scale users might be delegated to collective governance arrangements, with informal water rights recognized. However, in this case, the regulatory system will have to ensure that the rights of small users are protected against encroachment from large-scale users. Collective management may empower the small users to defend their rights.

5.2.3 Using the Incentive Structure
A second approach to changing groundwater behaviour is to change the incentive structure.

The purpose of this approach is to align incentives; that is, to put in place incentives for pumpers to align their behaviour with the government's policy objectives. Essentially, the changes open to governments are: (i) adjustments to input and output prices to affect the profitability of water use (especially in agriculture); (ii) subsidies to encourage specific abstraction and water use behaviour; (iii) bans to discourage undesirable behaviour; and (iv) facilitation of water markets to align the financial returns a well owner can obtain with the scarcity value of the groundwater in other uses.

Working through the incentive structure is generally attractive to governments because they often control the parameters involved (trade policy, agricultural policy, energy pricing). In addition, the administrative costs are low or zero and the impacts can be swift and considerable. The main disadvantage is that incentives are blunt instruments that can have many unintended or secondary effects. Moreover, behaviour responses may turn out to be different from or even the opposite of what was intended.

Table 3 gives some indications of the options available and of some of the advantages and disadvantages, which will help in determining when incentives may be appropriate ways to influence pumping behaviour.

Table 3. The Pros and Cons of Options for Changing Pumping Behaviour through the Incentive Structure

<table>
<tr><th>Options for adjusting incentives</th><th>Pros</th><th>Cons</th></tr>
<tr><td>Adjusting input prices influenced by government e.g. energy, fertilizer, seeds etc.</td><td rowspan="2">Within government power
Easy to administer
Immediate and universal impact
May generate fiscal revenue</td><td rowspan="2">Affects all sectors using the input (especially energy)
Raises consumer prices
Reduces farm incomes
May produce unintended effects*
May be inequitable (e.g. loss of employment)</td></tr>
<tr><td>Adjusting output prices influenced by government e.g. trade controls, cropping pattern controls, crop bans, taxes, official procurement prices</td></tr>
<tr><td>Subsidizing specific behaviours such as more efficient irrigation (drip, greenhouses, etc.)</td><td>Can increase farmers' incomes while reducing water use (more income per less drop)
Positive impact on GDP</td><td>Can be hard to administer
Can be expensive
Open to inequity and corruption
Does not necessarily reduce water use (Jevons paradox)**</td></tr>
<tr><td>Bans on specific irrigation techniques</td><td>May be easy to implement (e.g. ban on centre pivot)
May resolve a large part of the problem quickly</td><td>May be hard to implement (e.g. banning flood irrigation)
Direct impact on the value of farmer assets and incomes</td></tr>
<tr><td>Facilitating regulated water markets</td><td>Allows transfer to higher value uses
Profit incentive to comply
Relatively easy to regulate</td><td>Limited to wells near settlements
High cost of transporting the water
May be inequitable</td></tr>
</table>

* For example, raising diesel prices in Yemen led to a shift in farm crops from growing grapes and cereals to the production of the soft drug *qat*, as this was the crop that returned the highest income per drop.
** Jevon's paradox states that if the use of an input is made more efficient, using it is more profitable, so *more* of it will get used.

The introduction of regulated water markets is an appealing option for a number of reasons.

- It can facilitate the allocation of groundwater to its highest value economic use. Typically, the transfer would be out of agricultural uses (which normally return the lowest income per drop) to municipal and industrial uses (which have the highest value).
- It provides incentives to a well owner to transfer water to higher-value uses by raising the return per drop towards the opportunity cost.
- The government can more easily regulate traded water, as it must be conveyed by tanker or pipeline, and it can thus require compliance, for example with: (i) limits on total abstraction through metering and inspection; (ii) control of prices; and (iii) public health requirements.

However, many constraints limit the development of such markets.

- Water is very bulky and expensive to transport so the option only applies in the peri-urban hinterland.
- Pipeline conveyance is not usually economic because of the likely small volumes involved. As a result, transport is done by tanker, which is very much more inefficient in terms of cost.
- Although groundwater is usually individually appropriated, it has common resource characteristics that are inconsistent with all the revenue going to one well owner

Such markets do exist in many countries, usually informally, and for the tanker trade. Attempts to formalize these markets have been made in Jordan. In Yemen, rural-to-urban water sales by user associations have been piloted.

Other forms of incentives may be devised, depending on the nature of the problem. For example, payments for environmental services (PES) or an ambient tax or subsidy may be imposed.

Negotiated solutions for groundwater protection, such as payment for environmental services (PES), have been shown to be less expensive compared to top-down regulatory solutions. Another possibility is the ambient tax or subsidy, which penalizes or rewards a community if, say, the level of aquifer drawdown is greater or less than an agreed target (see Box 17).

Box 17. Adjusting Incentives for Groundwater Management in the Absence of Information on Individual Groundwater Use

There are multiple examples of cases where effective groundwater management has been implemented without needing to measure the behaviour of individual wells.

In India, regulation, water pricing or property right reforms are unlikely to reduce groundwater extraction because of the logistical problems of regulating a large number of small, dispersed users. However, *electricity supply and pricing policy* offers a powerful toolkit for indirect management of both groundwater and energy use. In France's Seine-Normandy river basin district, groundwater use for agriculture is not metered, instead fixed charges per hectare are levied.

Another viable incentive is the *ambient tax* or *ambient subsidy*. It is especially appropriate to groundwater in cases where it is virtually impossible to meter and monitor individual wells. An ambient tax on groundwater could be applied at the community or aquifer level against an observed variable (for example the groundwater level or the pollution level) that is affected by individual but not observable decisions (withdrawals, or non-point source pollution). The collective tax (or subsidies) is applied if the variable is above (or below) a specified target.

Ambient taxes have been studied theoretically but not yet applied in the groundwater sector. Some field experiments on biodiversity conservation in Ethiopia show that the high collective tax is an efficient and relatively reliable mechanism to solve the problem of excess exploitation of an open-access common pool resource.

Sources: Garduño *et al*., 2011; Acteon, 2009; Segerson, 1988, Giordana & Montgimoul, 2006; Reichhuber *et al*., 2009. Also see Annex 4.

5.2.4 Subsidiarity

Subsidiarity (water management at the level of the lowest feasible hydrological unit) is particularly appropriate for groundwater.

Subsidiarity delegates responsibility for management to the lowest feasible level. The nature of groundwater and the way in which it has been developed to date may make local management highly indicated. This is because groundwater resources management is made up of the behaviour of numerous individual wells, all of which share common resources. Changing management requires changing the behaviour of *all* wells, and this is most easily done at the aquifer level and below where the wells are few enough that they can be regulated as a group within a discrete hydrological unit.

Subsidiarity does not <u>necessarily</u> mean collective management, but there can be advantages to collective management approaches.

Local branches of ministries or agencies may be close enough to the ground to impose regulation. However, frequently the conditions of capacity and of respect for regulation are not in place. Under these circumstances, there are good reasons why the option of extending subsidiarity to local collective action may be considered. This would allow all the strengths of community management to be mobilized (knowledge, the incentives of self-interest and ownership, accepted patterns of water rights, social and institutional capital, and so on) in areas where water users are few enough that they can agree on self-regulation and where each pumper can see the benefits.

There are many examples where subsidiarity and collective management have proved superior to regulatory approaches, often in partnership between local government agencies and user groups.

The case studies provide a number of examples where local collective management produced good outcomes. In addition, the federal government in Mexico attempted to regulate groundwater abstraction, but they were unable to implement the policy for reasons that included inadequate operational resources, a failure to mobilize user cooperation, and an inability to enforce rules consistently. Instead, the Mexican government decided to support groundwater users associations. In Peru, the government issued water permits to user groups rather than individuals because of similar capacity constraints (Box 18).

Box 18. Water Rights in Peru

In 2004, Peru initiated the PROFODUA (Program for the Formalization of Water Use Rights) program to formalize water use rights. The program has an innovative approach, using water blocks (*bloques de riego*) and issuing individual or communal water licenses or so-called *licencias de agua* (permanent water rights for irrigated areas). The program was initially implemented in coastal regions of Peru and was developed gradually in close coordination with user organizations.

Through the approach based on water blocks, the program has issued an impressive number of new agricultural water licenses (more than 300,000), although many remain to be granted (there are 800,000 farms in the Pacific watershed alone). By issuing bulk rights to water user groups and helping them manage their individual user rights, the program was accelerated and institutional capacity constraints did not become limiting. Rights to use surface water and groundwater were issued in a coordinated manner, since both sources are closely linked in the coastal valleys of Peru.

Source: Vidal, 2010; Guerrero Salazar, 2009.

5.2.5 Choosing Governance Approaches

Each situation may require a different approach or a mix of approaches.

Table 4 gives an overview of the conditions necessary to each of the three approaches assessed in this section, together with an indication of which approach might be the most effective under the prevailing conditions. The lessons from Table 4 are that:

- there is no “one size to fit all,” and approaches need to be selected in the light of local conditions and experience
- rights and regulation systems are the most apt to achieve policy objectives, but they are also far and away the most demanding and difficult
- a mix of approaches is likely to be the best way forward in most country situations.

Determining the correct balance between governance options may take time and it is crucial to keep the options under review. There needs to be a mechanism for monitoring and evaluating the effectiveness of the measures deployed and for evaluating the transaction costs in relation to results. This process of evaluation can drive a joint learning experience involving all stakeholders, as well as procedures for incorporating lessons through adjustments to policies and to the governance framework. Pilot programs are a good way to test governance options. Groundwater projects may provide a good opportunity to test mechanisms for better management by, for example, piloting partnerships between collective management groups and government agencies.

Table 4. Governance Approaches to Groundwater

Requirements	Which approach may be the most effective?		
	Rights and regulation	**Incentive structure**	**Subsidiarity**
Is there a legal framework of rights and regulatory instruments that is adapted to the situation and which is implementable? If yes…	✓		
Is there a pattern of groundwater users complying with authority? If yes…	✓		
Is the approach administratively simple and low cost?	✓	✓	✓
Is there strong social capital and/or a history of agreed water rights and collective management at the local level? If yes…		✓	✓
Is inter-sectoral water transfer an objective? If yes…	✓		
Is there a serious depletion problem? If yes…			✓
Is there a serious pollution or recharge problem? If yes…	✓		✓

Changes to the governance approach can be made as experiences yield their lessons. In Yemen, for example, the 2003 Water Law and the 2004 National Water Strategy (NWSSIP) established the nation's groundwater policy and strategy. In 2008, an exhaustive participatory evaluation of the results was carried out that resulted in proposed revisions to the water strategy. The revisions were debated and agreed to in 2009 and the Water Law was amended to reflect the changes. Essentially, the changes put much more emphasis on collective management and local partnership approaches and much less on attempts at top-down regulation (which had proved largely fruitless).

Adapting Approaches to Implementation Capacity

When one of the main problems facing implementation is the issue of capacity, priority can be given to managing those aquifers that at risk (because of water quality and quantity) and to regulating the main users. For example, the analysis of water users in the Limpopo and Volga basins revealed that the few, often corporate, formal urban and rural users, accounted by far for the largest share of water resources, while the many small-scale farmers only used a tiny fraction of the nation's water resources. Capacity constraints mean that, in practice, governments can only regulate the larger operators through, say, a system of permits. The permit system can also be used to collect water resource fees or other charges (Van Koppen, 2010). This is the approach used in Saudi Arabia, where the unlicensed farm wells pay nothing, but the licensed industrial and oil sector enterprises pay a hefty resource charge.

Ensuring Equity

Fundamental to all groundwater governance is the allocation of water rights and how they are to be administered and protected. Rights and regulation approaches can ensure the protection of existing rights and can also provide a framework for secure transfer of rights, for example in water markets or in negotiated and compensated cession of water rights by farmers to a municipal water supply utility. However, the many constraints to implementing a full rights and regulation system mean that, in practice, most rights will have less formal protection and, as a result, they may be less secure and less tradable (Huntjens *et al*., 2012; Lebel *et al*., 2009a). *If a rights and regulation approach cannot be fully implemented, there may be risks to the water rights of others and water transfers or markets may be more difficult to implement.*

Collective management institutions may be able to protect rights and even enter into contracts for water transfers. However, this can only take place if the governance system is able to support such institutions. Based on analysis of water governance systems in the Netherlands, Australia and South Africa, Huntjens *et al*. (2012) argue that strong water user groups should be able to establish and protect water rights. Pilot programs in Yemen have shown that it is possible for water user associations to agree on rules for water transfer, including selling water to municipal utilities. If, as is likely, countries adopt a mix of rights and regulation and collective management approaches, the legal framework and the governance system need to protect less formal water rights and allow their transfer.

5.3 Information, Knowledge and Communications

Information, knowledge and communications are essential components of good groundwater governance. Groundwater management is a knowledge-based activity in which outcomes improve in direct relation to the coverage and quality of data. Knowledge is an essential input to planning for groundwater and to the design of appropriate governance systems. The communication of knowledge to all stakeholders is an essential guarantee of the accountability of sector institutions, and is the key catalyst of stakeholder participation and beneficial social change. For these reasons, countries have invested considerably in groundwater resource assessments and information systems, in using the results for planning and management, and in communicating results to policy makers, stakeholders and managers (see Box 19).

Box 19. Assessing Groundwater Balance in India

In India, the Central Ground Water Board carries out a systematic annual joint exercise with the state governments to assess the groundwater balance in the nearly 6,000 groundwater blocks. The blocks (areas of around 100 villages) are categorized according to the stage of their groundwater development from white (underdeveloped) to dark (critical and overexploited blocks where known groundwater resources have been fully or overdeveloped). Groundwater use is expressed as the annual groundwater draft as a percentage of net annual groundwater availability. The list of overexploited, critical and semi-critical blocks is circulated to the State Pollution Control Boards and the Ministry of Environment and Forests. Those agencies also refer new industries/projects to the Central Ground Water Authority (CGWA) for obtaining clearance for groundwater withdrawal.

This has been an essential tool in mapping groundwater conditions in India and creating awareness among decision makers. One limitation of this exercise is that the units used for the groundwater assessment are administrative units, mostly at the sub district level, without any link to physical or aquifer boundaries.

Typical Impediments to Data Collection

Information on groundwater resources is key for decision making in the sector. However, the lack of adequate data and appropriate information systems remain major constraint in many countries. The cases studied highlight several challenges to the collection, analysis and dissemination of information, including: high costs, the large number and diversity of users, little understanding of uses and user behaviour, and lack of capacity and skills.
The collection of information on groundwater is costly. Describing the structure of the geological layers and their hydraulic characteristics requires expensive specific studies to assess the complexity of three-dimensional groundwater systems. The case studies in Chapter 3 show that at least some information on aquifers is often available in areas where groundwater is already being used. However, detailed information on groundwater balance and on sustainable yields is often lacking, due to several constraints:

- Understanding groundwater dynamics involves a continuous monitoring to capture inter- and intra-annual variations of groundwater levels, and this requires the significant allocation of human and financial resources.
- Elements of the groundwater budget (such as recharge, irrigation return, and exchanges with surface water or with other aquifers) might be difficult to assess because they are variable in space and time.
- A further problem is that, even when information is available, it is often difficult to interpret. Even the concept of a safe or sustainable yield is controversial and requires a clear definition between practitioners when discussing groundwater management objectives (You, 2009). Overall, the general inadequacy of monitoring and evaluation stems in large part from a lack of incentives for stakeholders to expend financial and human resources on something that may only reap rewards in the longer term.

The large number and diversity of users make it difficult to collect data on groundwater use and users. In India, for example, there is no systematic registering of wells and gathering data about millions of private well owners is impossible (Garduño *et al*., 2011).

Third, even if there is adequate information about the resource, there is usually too little understanding of uses and user behaviour to develop adapted governance arrangements. Simply understanding groundwater resource dynamics does not explain why changes are taking place, or how those changes may evolve. Yet, that information is essential to defining governance and management arrangements. Insufficient effort has been made to collect information on groundwater use and on the socioeconomic characteristics of users in order to adapt governance arrangements.

Groundwater management thus requires knowledge of users and their objectives. Knowing the users, and taking into account the local incentives framework as well as the opinions, interests, perceptions and willingness to change of stakeholders are therefore vital to creating a groundwater governance solution. Also important is understanding how groundwater use is embedded in the local political and economic context. Knowledge (or its lack) may also influence groundwater use. For example, groundwater is often thought of as an inexhaustible private resource, which makes users loath to reduce pumping.

There is lack of capacity and of the interdisciplinary team skills (including sociological skills) needed to collect and analyse information about groundwater. The case studies in Chapter 3 show that human resources are often lacking, and that specific attention should be paid to attract and retain experts. With the growing importance of participation and collective action in groundwater management, social expertise will increasingly be needed to promote constructive dialogue between engineers, social scientists, environmentalists and economists within government agencies. Tools used to implement integrated water resource management, such as encouraging multi-disciplinary training for practitioners (GWP, 2008), could be used to help address this issue.[24]

Impediments to Turning Information into Knowledge
Once information is collected *it has to be standardized and transformed into knowledge* to be useful for management purposes. Evidence from case studies indicated that the allocation of financial and human resource to facilitate this is limited. This lack of resources, in turn, limits the decision support tools available. For example, in Tanzania the problem is the very limited sharing of data on groundwater, which also limits data analysis. To remedy this situation, the use of computerized systems and the standardization of formats are recommended. The problem in South Africa is that groundwater database or information systems are maintained by different institutions (including the private sector). This hinders compatibility and the inter-agency exchange of data. Of the five countries studies, only Morocco has a decision support system based on groundwater models that are used by managers.

Impediments to Communications
Once the information is collected and transformed into knowledge, the next crucial step is to communicate it effectively to foster the participation of relevant stakeholders. However, evidence shows significant gaps in communication capacity that has constrained participation at all levels.

Moreover, there is also weakness in the effectiveness with which the results of data collection and knowledge are communicated to stakeholders (both users and polluters). Although the dissemination of information is vital to promoting transparency and helps to build understanding and support from the community, there is a generally low level of public awareness about groundwater. A recent review of IWRM in Africa (AMCOW, 2012) cites "low levels of awareness among different stakeholders" as the third most frequent constraint to IWRM development. For example, despite having one of the best monitoring systems among the countries studied, along with the key expertise to analyse the data and develop hydrogeological models, efforts in Morocco are thwarted by a lack of effectiveness in the communication of information. A 2007 survey (JICA, 2007) in the Haouz aquifer area revealed that few farmers had any knowledge of the regulations concerning abstraction permits, drilling of wells, or installation of meters, and that only 15 percent of farmers believed it necessary to conserve water. Despite improved platforms for data availability (such as the Internet), without dissemination campaigns or user participation in groundwater monitoring, communication to users may still be limited.

The problem is often compounded a lack of willingness on the part of the government to share information publicly. This may be linked to centralizing governance arrangements, or to reticence about stakeholder involvement and participatory approaches. Conversely, such historical legacies can also lead to a lack of trust by local communities of higher level institutions.

[24] GWP 2008. Toolbox for Integrated water resources management website. Available at http://www.gwptoolbox.org/index.php.

The unwillingness to share information is often exacerbated in the case of transboundary aquifers due to the reluctance of national governments to exchange data and information with their counterpart administrations because of strategic considerations. Saudi Arabia is an example of a nation where groundwater is of utmost importance, and despite comprehensive hydrogeological and monitoring records of many systems, the information is not shared beyond national boundaries. Yet, in the context of transboundary groundwater systems, information exchange between countries is a first step towards effective management. The need to start working towards practical and effective transboundary agreements for groundwater governance between countries is emphasized by AMCOW (2012), which found at least 38 major transboundary aquifers in Africa, occupying 64 percent of the total land area.

Options for Removing Impediments

Overcoming Barriers to Information Collection and Management

Countries need to invest in improving their knowledge of the physical characteristics of aquifers, and in the continuous monitoring of groundwater quantity, quality and uses. Case study countries, especially South Africa and Morocco, have already undertaken significant measures to improve information on aquifers and establish a monitoring network. Already overused aquifers should be given priority, particularly where stresses are apparent. Future groundwater development projects should establish a viable information collection, storage, analysis and reporting system, paying special attention to how the system will be financed once project implementation is complete.

To lower costs and improve communication with users, India has carried out experiments with participatory monitoring of groundwater. The results have been promising in term of providing farmers with the necessary knowledge, data, and skills to understand and manage groundwater resources without offering any cash incentives or subsidies. Another interesting experience has been observed in South Africa where, to improve data collection and communication, the government developed a nation-wide system of scores to monitor the status of water quality management (drinking water and wastewater, Box 20). Collecting and communicating information in this way ensures accountability of water service providers to the users. To date the program has already resulted in significant improvements in the provision of water services for domestic supply.

A number of innovative approaches have been developed with the advent of satellite and aircraft borne sensors. For example, evapotranspiration from crops can be estimated using remote sensing data using algorithms that have been developed over many years (Kalma *et al.*, 2008). Groundwater use can then be estimated if surface water use is known. This method is applied in China to manage groundwater use for irrigation. The technology provides a cost-effective solution to monitoring groundwater use of large number of users. In the China case, a basin-wide application of remote sensing evapotranspiration measuring technology was introduced in the Hai Basin to limit groundwater overdraft and control quotas of groundwater consumed by irrigation (World Bank, 2011b, see Box 14). Another interesting example is the GRACE satellite system, which measures changes in groundwater volumes at a regional scale using extremely sensitive gravity anomaly satellites (Becker, 2006). While the spatial scale currently limits its operational relevance, this technique opens up a path for future applications. Lastly, airborne geophysical methods allow groundwater salinity to be mapped from an airplane. This has been used to locate land salinization across broad areas of Australia and could be used to help monitor progress of salt water intrusion in coastal aquifers. While all these parameters can be obtained through traditional ground-based methods, *remote sensing approaches provide coverage of large areas at a fraction of the cost of traditional methods.*

Knowing the users and their interactions

Increased attention should be paid to information on groundwater uses and the socio-economic characteristics of the users (direct and indirect users).

This will guide the formulation of public policies by informing decision makers on not only the number of users but also on the current property rights, the existing informal arrangements between users, their perception of the resources as well as their willingness to change. Collecting and analysing this type of information requires specific capacity which could be enhanced by setting up multidisciplinary teams that include social scientists.

Box 20. Monitoring Water Quality and Communicating Results in South Africa

In 2008, South Africa's Department of Water Affairs (DWA) introduced a nation-wide incentive based regulation process to monitor the status of drinking water quality (DWQ) management (the "blue drop system"), and wastewater quality (WWQ) management (the "green drop system"). The aim was to improve the operation and functioning of water services institutions. A so-called drop score is calculated based on a weighted set of criteria and the results are published in DWA blue and green drop reports, and on the DWA web-site (www.DWAF.gov.za) which is open to the public. The blue drop score for DWQ management, for example, is based on the following set of criteria (percent weighting appears in parenthesis):

- Water safety plan (5 percent)
- Process control and maintenance competency (10 percent)
- Efficiency of drinking water quality monitoring program (15 percent)
- Credibility of sample analysis (5 percent)
- Regular submission of DWQ data to DWA (5 percent)
- Drinking water compliance with the South African National Standards (SANS 241) (30 percent)
- DWQ failure response management (15 percent)
- Responsible publication of DWA asset management (5 percent)
- Efficacy of basic DWQ asset management (10 percent)

Once a water services authority scores higher than 95 percent it receives a blue drop status. For the green drop status the score has to be higher than 90 percent. Blue or green drop status will allow consumers to drink water from the taps in the town with confidence, and be secure in the knowledge that wastewater is managed and discharged in a sustainable, environmentally-acceptable manner.

Source: Pietersen *et al*., 2011.

Programs of regulation or subsidy can be used to set up a systematic knowledge system.

Licensing wells and providing groundwater use rights is often a first step toward a better knowledge of groundwater users. For non-exploited resources, new wells can be registered through agreements with drilling companies. For already exploited resources, the task is more challenging. A possible mechanism to get the information is to deliver grants and funding with the condition of providing information on wells and groundwater use. Crop subsidies are used for this purpose in the Beauce area in France (see Annex 4).

Partnerships with local collective management institutions can also generate knowledge.

Another option consists of relying on local formal or informal institutions as partners, for example in monitoring abstractions or to inventory wells. This can be part of the collective management approaches described in Chapter 6.

Monitoring and evaluating groundwater management measures

The information system should also include M&E of the outcomes and impacts of policy and of the performance of the governance system.

Monitoring and evaluation of actions related to groundwater management and governance should be included in the information collection and management system (e.g. projects and programs at both local and national levels). Accountability and performance efficiency only work if performance against the agreed standards is regularly measured, and poor performance is penalized; this requires functioning systems for monitoring and evaluation. Policy evaluation may require long-term monitoring. For example, experience in Europe shows that the evaluation of agri-environmental measures, which aim to reduce groundwater non-point agricultural pollution, is a long-term and difficult process given the physical complexity of agriculture impact on groundwater (including the time of pollution transfer and the influence of climatic variables) (OECD, 2010).

Facilitating communication and participation

Communication can foster participatory approaches and catalyse social change.

'Water governance is as much about the art of social change as it is about the science of hydrology' (Currie-Alder *et al.,* 2006). Improved communication may help facilitate participation and social change, particularly by sharing knowledge to increase the understanding of 'invisible' groundwater resources and improving the accountability of institutions at all levels responsible for groundwater management.

The three Ds of transparency need to be promoted: disclosure, demystification, and dissemination.

Communication strategies should be based on the three dimensions of transparency: (i) disclosure of information; (ii) demystification (strengthening the level of awareness and understanding); and (iii) dissemination to the public (World Bank, nd). Mechanisms promoting transparency for groundwater-related schemes may include: posting physical information (water levels, abstraction volumes) in newspapers and on community public posting boards; explaining groundwater-related financial budgets to the community; opening contracting arrangements, reports and decision-making to public scrutiny; publishing performance and annual reports from local governments and regulators by using media[25] or community radio; and organizing public hearings where stakeholders can share claims, problems, and reach reasonable solutions (WBI, 2009a). Additionally, the Africa IWRM report (AMCOW, 2012) recommends establishment of a 'good practice guide' to facilitate sharing of water-related knowledge among stakeholders to promote capacity development, transparency and cooperation.

More generally, transparency and dialogue strengthen governance and improve outcomes.

Multi-stakeholder dialogues, including social learning processes, negotiation and co-production of knowledge are crucial for effective and legitimate water governance and are cross-cutting many of the design propositions discussed in this report. In Lebel *et al.* (2009b) multi-stakeholder dialogues are defined as "events at which different stakeholders openly engage in facilitated, informed, deliberations". The purposes (and values) of these dialogues are: (i) to reduce conflicts and explore synergies; (ii) explore alternatives; and (iii) shape and inform negotiations and decisions (Lebel *et al.*, 2009b). During these dialogues it is important to produce outcomes that are directly relevant for planning and decision making. Stakeholders should therefore be involved in analysing and synthesizing project and process outcomes as well as identifying best practices for governance and implementation (Huntjens *et al*., 2012).

5.4 When things go wrong: conflict and conflict resolution

Because groundwater extracted by tubewell was a new and abundant resource, the early stages of the groundwater revolution saw little conflict – but this is now changing.

In the early stages of the modern groundwater revolution, there was little or no 'conflict', as in most situations the right of individuals to drill boreholes on their own land was accepted and the resource was abundant. Over time, the resource has depleted and in many situations, people are aware that a neighbour's borehole or pumping behaviour will affect others. In some cases, the 'cone of depression' of the sinking water table has spread over hundreds of kilometres, causing extra costs for everybody for deepening wells and pumping from increasing depths. At the limit, some sources have dried up. Plainly this creates potential for dispute, and there are cases of violent conflict (for example in Yemen and Iran).

However, conflict has typically been much less in the case of groundwater than of surface water.

This is for several reasons inherent in the nature of the resource and the way in which it is exploited:

- Even if negative changes are occurring, they are relatively slow to emerge and supply remains predictable, so there is no 'decisive moment' that might provoke conflict unlike, for example, upstream diversion of a water course.
- Groundwater is individualized, and there is no necessary involvement of any third party that may cause dispute, unlike for example disputes over 'turns' at a surface water canal

[25] A free and open media should be encouraged where possible.

- Groundwater is invisible, so that disputable changes in the system are hard to spot, even for a hydrogeologist, unlike for example a dried-up oasis
- There is no apparent symmetry of cause and effect, as one individual's pumping behaviour is hard to link to the long term decline of a vast underground water body unlike, say, construction of a dam upstream

Nonetheless there are many potential sources of conflict.

Potential sources of conflict over groundwater are multiplying as over-exploitation of groundwater resources results in declining water levels, and as water quality declines through contamination and salinization. Based on the case-study reports, different types of conflict related to groundwater management have been identified:

- Conflict due to groundwater pollution (e.g. in Kerala State, India, where Coca Cola Beverages Company had to pay compensation to the local community for over-exploiting the groundwater resources and discharging pollutants into the water)
- Conflict due to groundwater over-abstraction (for example in Yemen, see Box 21)
- Conflicts between countries, and within countries, over access to shared groundwater resources (see Box 22).
- Inter-sectoral / inter-basin conflicts (e.g. in Tanzania)
- Conflict regarding roles and responsibilities (e.g. in Kenya)
- Conflicting land uses, for example in Tanzania, land use planning rarely considers groundwater resources potential, and it is common to find encroachment and land uses that limit recharge in aquifer rich areas where groundwater could have been exploited.
- Conflict between farmers and public agencies over regulation, e.g. over abstraction fees in Morocco.

Box 21. Upstream prospers but downstream area desolate and angry in Yemen's Wadi Bani Khawlan

The upper part of Wadi Bani Khawlan in Yemen's Ta'iz Governorate is covered with crops and lush fruit trees, irrigated from tubewells. The lower area of the wadi, once also a rich agricultural zone, is now desolate. Dry wells dot the fields. In some areas, pipes still cross the ground ready to transport water to waiting fields, should water somehow return to the wells. In most areas, however, the pipes have been removed—sold since they no longer serve any purpose. Where wells still operate in the lower wadi (mostly at points at which minor side wadis enter the main one), women wait for 6–7 hours daily to fill up plastic containers of water for domestic use. Protest and armed confrontation proved useless to stop the upstreamers from drilling ever more wells – the upstreamers were stronger. Now most men from the lower wadi have migrated in search of work, joining a disaffected population in the slums of Ta'iz. A few remain, spending their time and the remittance money sent by others in the small dusty stores that are remnants of more prosperous days in the valley.

Source: Moench, 1997 *In*: Ward & Al-Aulaqi, 2008.

The changing institutional context, power relations and the intensification of conflict
New tubewell technology and the rapid over-development of resources have produced a pattern of inequitable access to groundwater.

Asymmetrical power has led to asymmetrical access to water. Water "flows uphill to money and power" (Reisner, 1993), and the political economy of many groundwater-dependent countries – for example, those of the Middle East – does not provide for the accountability mechanisms or educated participation in decision making that would promote more equitable outcomes. Restricted access to land also limits access to water, for instance through increased privatization of public or endowment land by powerful interests at the expense of poor and vulnerable groups (such as the rural or landless poor).

Climate change is introducing costs and risks that are hard to manage, including increased demand for groundwater and reduced recharge, with consequent heightened risk of conflict.

In the Middle East, for example, which is highly dependent on groundwater, high variability and low means in rainfall, exacerbated by climate change, have led to unpredictable, declining water resources, variations in supply, and increased disasters, such as floods, drought, etc. The prospect of further climate change is likely to exacerbate these stresses. According to the Intergovernmental Panel on Climate Change, a precipitation decrease of over 20% can be expected over the next century for large parts of the MENA region, as well as a likely increase in the frequency and severity of droughts and a reduction in groundwater recharge rates. On the demand side, declining water availability and rising demand is likely to place ever greater stress on already over-exploited groundwater resources and lead to greater risks of conflict. (World Bank 2007; CEDARE, 2006)

Box 22. Potential for conflict over transboundary aquifers needs to be handled by joint study and subsequent mutual agreement

In 1983, Libya initiated a huge civil water works project known as the Great Man-Made River (GMMR), a massive water transfer project that draws from fossil aquifers deep below the interior Sahara to deliver more than five million cubic meters of water per day to cities along Libya's coastal belt. The GMMR has been a source of international tensions within Africa, as the Nubian Sandstone Aquifer (NSAS) is the world's largest fossil water system, which straddles the borders of Libya, Chad, Egypt and Sudan, covering some two million square kilometres and estimated to contain 150,000 cubic kilometres of groundwater. The diversion of this non-renewable resource north to Libya's capital has raised concerns about regional ecological impacts.

Nonetheless, the four NSAS countries have embarked on a process to cooperate on the management of the NSAS water resources. This regional cooperation is built on agreements on data sharing, monitoring and exchange with incorporation of data in a regional information system. In addition, in 2005, the Nubian aquifer project (IAEA/UNDP/GEF) helped establish a rational and equitable management of the NSAS for sustainable socio-economic development and the protection of biodiversity and land resources.

The World Bank also faced the issue of transboundary groundwater in 1997 with the Disi-Amman Water Conveyor Project. The Disi aquifer is a fossil, non-renewable aquifer which underlies both northern Saudi Arabia and southern Jordan. Jordan had to notify Saudi Arabia of the project, who asked that no well should be drilled within 15 kilometres of the borders in each country.

In South Africa there are some important areas of higher-transmissivity transboundary aquifers shared by South Africa with Botswana, Zimbabwe and Mozambique, such as the alluvium associated with the Limpopo River and areas of dolomite such as the Pomfret-Vergelegen dolomite aquifer. These aquifers do have the potential for transboundary conflict over shared water, and need to be managed with care. Better data collection, and improved sharing of data, are likely to be central to mitigating and resolving any future conflicts.

Source: Cobbing *et al.,* 2008; DWA, 2010; Jarvis, 2006; Salman, 2009.

Development of transboundary aquifers may be inequitable and lead to disputes.

Emerging nations have begun to assert rights to shared transboundary aquifers, whilst more powerful nations have developed the resource unilaterally without any comprehensive agreement on benefit-sharing. Already, some possible disputes have emerged, for example over the Nubian Sandstone Aquifer and over the Disi Aquifer between Jordan and Saudi Arabia.

Dispute resolution mechanisms today

Traditional governance mechanisms have difficulty in adapting to the tubewell, but some are showing 'adaptive capacity'.

In many countries it is clear that traditional water governance systems, set up to deal with springs or *qanats* or run-off or spate flows or hand-dug shallow wells, have little capacity to deal with disputes over tubewells (see Box 23 on Wadi Dahr). Nonetheless, there are examples of traditional systems adapting – for example, many communities in Yemen have revived an old customary law on well spacing and increased the regulated distance between wells to up to one kilometre.

Box 23. Conflict, adaptive capacity and a shifting equilibrium in Yemen's Wadi Dahr

Yemen has an age-old history of water conflict and of subsequent accommodation of change. Wadi Dahr, close to Sana'a, had a long, well-documented history of managing its water resource. Rules had been agreed over centuries through an evolving process of conflict, contentious judgments, and ultimate development and acceptance of new rules that progressively crystallized into "established tradition".

In 1970, the tubewell burst into the finely balanced water economy of the wadi. A downstream community in the wadi complained to sheikh's court that upstream motor pumps had reduced the stream flow and disturbed "laws and customs…by which we have been guided for thousands of years."

This new conflict got resolved — but not by the courts. The rich and influential downstream farmers simply invested in the new pump technology themselves. "The stream dwindled and died, but no one with influence any longer cared." A new equilibrium emerged: assets were rebalanced and concentrated a little more in the hands of the richer. The conflict was resolved — even if not fairly — and a new "established tradition" emerged.

Sources: Mundy, 1995.

A few modern dispute resolution mechanisms are being set up, sometimes alongside the old, but with mixed results.

In general, governments have not developed the flexible and participatory institutional mechanisms and accountability structures needed to respond to emerging groundwater conflicts. Where new systems of dispute resolution have been established, results have been mixed. In some cases, governments are introducing modern forms of dispute resolution but are unable to fully implement them. For example in Kenya, a new formal mechanism of conflict resolution has been set up but has never heard a single case, whereas older traditional mechanisms continue to be effective and modern user associations are also showing their ability to settle disputes (see Box 24). In some cases, these introduced forms of governance can undermine traditional governance systems. This creates a "hybrid governance system" that can even increase conflict.

Box 24. In Kenya, a modern Water Appeals Board has never heard a case in ten years – but modern user associations at the local level appear more effective in resolving disputes

To help resolve a new generation of disputes that was emerging, the Kenyan government set up the Water Appeals Board. However, it is barely active. Rampa (2011) found that "modern complaint and feedback mechanisms are extremely weak, often cumbersome and undermined by the informal arrangements so common in the sector. The formal mechanisms often do not work, and the Water Appeals Board, mandated to handle disputes in the water sector, has not heard any case since its establishment with the 2002 reforms.'

By contrast, a number of Water Resources User Associations (WRUAs) in Kenya are reported to be effective in resolving water use conflicts, particularly in those catchments which are prone to water use conflicts. However, WRUAs are voluntary associations and therefore they are not uniformly spread across the country. Groundwater management WRUAs are rare, although two groundwater-specific WRUAs are under formation in the Tiwi and Gongoni areas in the Athi catchment; and three exist in the Tana catchment (at Lamu, Hindi and Mpeketoni/Lake Kenyatta).

Source: Rampa, 2011.

Solutions

Good governance capable of flexible and adaptive responses is the best way to solve disputes – even before they start.

A first approach is to ensure good water governance that will either prevent conflictual situations from emerging, or will have the adaptive capacity to change and to remove the cause of conflict. A good example of this is the evolution of a new water governance system in Western Australia to solve a conflictual situation between water resource management and water using sectors (see Box 25).

Dispute resolution mechanisms may be modern or traditional, centralized or local – the key criterion is that they be accepted as fair by all parties.

As disputes will inevitably occur, it is essential to have in place mechanisms for conflict resolution that are accepted as fair by all parties. These may be traditional (such as that in Yemen, see Box 26) or modern. In situations where there is confidence in the judicial system, water courts are an option. Where principles of subsidiarity are being applied, 'modern' water user associations may be formally or informally mandated to resolve disputes.

Box 25. In Australia, a long and involved process was needed to resolve the conflict between water management and the water using sectors

In Western Australia, the roles of water service providers were separated from water resource managers in 1996. The objective of this change was to ensure that water resource management took into account all water needs and that allocations were not subjectively biased towards public water supply. This was a fundamental change to organization and human relationships which had required a long and painstaking participatory process to resolve. The process culminated in a series of water forums and the 'Premier's Water Symposium' in 2002. The State Water Strategy, the establishment of a Ministerial Water Council, a new Office of Water Strategy in the Department of Premier and Cabinet and the Premier taking responsibility for water were all important steps in resolving conflictual issues in water management in Western Australia.

Source: Huntjens *et al.*, 2012.

Box 26. Traditional resolution of water disputes in Yemen's tribal areas

In Yemen, resolution of water conflict in tribal areas follows a traditional pattern. In case the conflict has turned violent, which is common, any respected person (*modareek)* can call a cease fire. There is then a mediation process, often by the clan head (*aqil*)) or the head of the tribe (*sheikh*) to agree the terms of a truce, and to broker an ultimate settlement. In case of legal technicalities, a tribal specialist of customary rights and duties (*maragha*) can be called in – his decision is final.

Source: Al-Shaybani, 2005.

Good models for transboundary aquifer management and dispute resolution can be found in various river basin initiatives.

Transboundary water management to resolve or avoid disputes can follow good practice that has been established in a number of river basins worldwide, including the Indus, Mekong and Nile basins. Only a few treaties and agreements address transboundary aquifers. On the basis of a survey of 400 freshwater treaties and agreements, about 15% were found to include provisions for groundwater (Jarvis 2006). Of the over 240 transboundary aquifer systems mapped across the world, only the Guaraní Aquifer System in South America (see Box 27), the Nubian Sandstone Aquifer System in North Africa (see Box 22), the Northwest Sahara Aquifer System, and the Lullemeden Aquifer System in Africa have embarked on cooperation.

A number of lessons can be drawn on how to avoid or resolve disputes on transboundary water management.

Best practice in transboundary water management and conflict resolution seeks to achieve the goals of fair distribution of benefits, economic efficiency and environmental sustainability through agreement on some level of cooperation. Lessons on the <u>process of negotiating cooperation</u> on transboundary waters show that it is essential to act early, that time and stamina are needed, and that communications, transparency, and stakeholder inclusion are vital. Lessons on <u>tackling the substantive cooperation issues</u> show that there is a need to analyse the political economy and to form strategies to overcome 'political economy' opposition. A progressive and flexible institutional strategy is needed. Typically, the process proceeds in a sequence, working from technical cooperation towards institutional and political cooperation – this allows confidence and habits of joint working to develop, whilst generating essential knowledge. The economic strategy should concentrate on sharing benefits rather than on sharing water. Here, early identification of one or two joint multi-purpose operations is helpful, as they could bring evident economic benefit.

Box 27. Sustainable integrated management of the Guarani Aquifer

The Guarani Aquifer is a huge hydrogeological system that extends over 1,200,000 km^2 across Brazil, Paraguay, Uruguay and Argentina. The total volume of freshwater is estimated around 40,000 km^3. The current level of exploitation is relatively modest, with total groundwater production estimated to be in the range 1,000-3,000 Mm^3/yr and mainly concentrated in Brazil. However, the aquifer is of growing importance in the potable water supply of towns of the region.

The GEF funded Guarani Aquifer Program (2002-2008) helped develop a comprehensive management framework, where sustainability and environmental concerns figure prominently, especially those with transboundary repercussions. In August 2010 Argentina, Brazil, Paraguay and Uruguay, countries that share the Guarani Aquifer System (GAS), signed a new agreement for the management of this complex system. The four countries are now involved in the ratification process and in the negotiations of institutional aspects, including discussions regarding an annex to the Agreement on arbitration procedures.

In addition, the project aimed to improve knowledge about the aquifer, as well as promote concrete management actions at the local scale, with the necessary level of transboundary integration. One of the project outcomes was the understanding that management of the aquifer is essentially a local set of activities; joint coordinated management is not needed for the entire aquifer. There was insufficient information and knowledge basis (aquifer extent, geology, hydrogeology, hydrogeochemistry, flow dynamics, age of water, etc.) prior to the Project to be able to reach this understanding and conclusion.

Four groundwater management pilot projects were funded through the Project. In each pilot area, the Project first established a Local Management Commission composed of several agencies and stakeholders. Later these commissions were transformed into 'Support Groups for Local Management of the GAS.' At present they have an information system with all the relevant data for the entire system, including well characteristics, water quality, level of extraction, and other relevant data for monitoring the aquifer.

Source: World Bank, 2009.

6. The Role of Participation and Local Collective Management in Good Groundwater Governance

Chapter 5 discussed 'subsidiarity' – delegating water management to the lowest feasible level - as a governance approach particularly suited to groundwater and indicated that participation and local collective management can, under some circumstances, be the most effective approaches to good water governance, or at least play a key role in good governance. These approaches are particularly important because they may offer solutions to many of the challenges presented by other governance approaches. This chapter therefore assesses in more detail the pros and cons of participation and local collective management and the options open to countries and stakeholders.

6.1 Why is Participation Particularly Appropriate in Groundwater Management?

Participation can improve outcomes because it increases stakeholder ownership…

As outlined in Chapter 5, the basic rationale for factoring participation into groundwater governance is that the goal of aligning groundwater management at the local level with policy objectives requires changes in the behaviour of <u>all the wells</u> in a groundwater management area, and hence requires the cooperation of <u>all the stakeholders</u> who are pumping out the groundwater or benefitting from it. Essentially, groundwater management cannot work without taking into account stakeholders' information and perspectives and without their collaboration.

Stakeholder involvement and 'buy-in', or ownership, is crucial for identifying acceptable trade-offs, for negotiating distributions of costs and benefits and for reaching consensus (Ashby, 2003). This form of ownership often needs to be established across a range of institutions and levels of decision-making (Martin and Sutherland, 2003).

…and because stakeholders often have access to information and can devise solutions better than or complementary to those delivered from the top down.

A second reason for involving stakeholders is that their involvement is key to coping with the complexities and uncertainties of groundwater governance, by bringing in a wider range of perspectives on needs, impacts and options, and having them deliberated openly (Huntjens, 2011). Local well owners and groundwater users have knowledge about the technical characteristics, about how water is used and why, and about the local governance institutions like water rights, collaborative management arrangements, water sharing agreements, provisions for sustainability such as well spacing rules, and so on.

Perhaps the most important aspect of participation is that it can align objectives of government with those of local people, so giving local stakeholders incentives to good groundwater management.

Well owners and local groundwater users reasonably view groundwater as <u>their</u> resource, whatever the legal texts might say, and these local stakeholders will have their own 'policy objectives' for development and use of the resource, for example: maximizing household food self-sufficiency; increasing income from sales of cash crops; assuring the village potable water supply; maximizing groundwater abstraction before the resource runs out, and so on. These objectives may be the same as government's policy objectives (e.g. sustainability, efficiency, equity) or – as is usually the case – they may be at odds with the 'top-down' view of how things should be done. Since each well owner is virtually sovereign over his or her pumping behaviour, government will never achieve its policy objectives unless <u>local people's objectives and the government's objectives are aligned</u>.

Participation can thus help to align objectives and then empower local stakeholders in subsequent implementation by giving them influence over outcomes.

This alignment of objectives is essential to providing the incentives to local stakeholders to manage groundwater well. Here the role of participation is twofold: informed exchanges to align objectives; and collaboration on achieving those objectives. Evidently the scope for participation in local groundwater governance is vast.

Local collective management is also more likely to take account of the needs of future generations.

In addition, participatory approaches, which empower local people by giving them influence over outcomes may improve sustainability. If a well owner is convinced that changing pumping behaviour will slow or halt resource depletion, he or she may well collaborate in collective groundwater management, taking account of the needs of his or her children

6.2 The Range of Participatory Approaches

Experience shows a whole range of participatory approaches to groundwater management, from 'consultation' to fully delegated groundwater management. Table 5 below lists some of the main approaches in order of progression from 'top down' to 'bottom up', and in sequence of increasing intensity of participation and empowerment of local stakeholders.

Table 5. Participatory approaches

Nature and level of participation	Typical organizational set up	Level of empowerment
Data collection	Local water resources management agency consults local stakeholders to obtain information	Negligible
Consultation about national or local water strategy	Consultants or planners consult focus groups	Low
Government launches projects to address specific management issues e.g. irrigation agronomy, water use efficiency, rural water supply	Project team works with a contact group or project-specific user group	Moderate
Participatory water resources planning e.g. for a local catchment	Local water resources management agency works with a stakeholder user group or traditional community group	Moderate
Collaboration on specific water resource management functions e.g. reciprocal data gathering and sharing		
Partnership to implement a local water resources management plan	Local water resources management agency works with a user association or traditional community group, providing knowledge, capacity building and support to self-regulation by the association	High
Water resources management delegated to stakeholders	A local user association or federation of associations takes responsibility for local aquifer management and self-regulation, with technical support from the local water resources management agency	Very high

Clearly the level of participation will depend on the local context, with the need for skilled support increasing as participation moves towards local collective self-management

Stakeholder ownership and incentives increase with the level of participation. However, there is a key role for public agencies at all levels, and this role requires increasing levels of skill at each successive level, until the last two (high, very high) levels in Table 5, which call for:

- Water resources assessment and monitoring skills to advise on planning and management for resource sustainability
- Social and institutional skills to support development of governance institutions at the local level
- Technical skills to advise on efficiency of water allocation and use.

A certain humility of approach to participation is in order
Groundwater planners naturally tend to think of participation in terms of 'permitting' increasing degrees of stakeholder participation in the governance, planning and management set ups which government has determined. But the reality is – the default option – that groundwater governance, planning and management arrangements are at present almost entirely in the hands of the local stakeholders who decide how much water to abstract – and often whether to drill another well or two. In this sense, Table 5 could be reinterpreted as levels of participation by government agencies in local governance arrangements. Participation is as much – or more – a way for public agencies to share in and strengthen local governance arrangements as it is for local stakeholders to be factored in to government's governance set up.

6.3 What are the Impediments to Participation and Local Collective Management?

Generally inadequate arrangements for stakeholder participation at the basin/major aquifer level
Frequently, the legal and institutional provisions do not empower collective management institutions

Case study analysis shows that despite the notional integration of participation in the strategies and regulatory frameworks of several of the study countries, the corresponding institutional arrangements for participation at the basin or aquifer level and below are not adequate. According to Ostrom (2005) most individuals affected by operational rules should be able to participate in modifying them. In large-scale resource systems such as a river basin or major aquifer, it is important to enhance the participation of those involved in making key decisions about the system (Huntjens *et al.*, 2012).

Several countries have made efforts to provide for stakeholder consultations at the basin level – and by implication at the aquifer level. However, results in the case studies were disappointing, with little or no focus on groundwater aspects of water resources management, and apparently stakeholders consulted having little influence over the outcomes (see Box 28).

At the local level, some activities for groundwater management may be undertaken by stakeholder groups along with other water resources.

Box 28. In Kenya, local stakeholders take part in panel consultations on water resource management issues in each catchment – but are not really empowered, and do not (yet) focus on groundwater issues

In Kenya, catchment area advisory committees (CAAC) were established under the Water Act, to advise regional managers of the Water Resources Management Authority (WRMA) on water resources management issues in the catchment. The CAAC has a statutory membership of fifteen persons drawn from stakeholders including sectoral institutions in government, the private sector and civil society which are relevant to water resources management. Members may be drawn from the ministries responsible for lands, forests, mines, agriculture and others. Non-governmental organizations working in the area of water supply, many of whom construct boreholes, could also be represented. However, in the current membership constitution of CAACs no special attention has been paid to representation by persons dealing particularly with groundwater management issues. This is the case in the catchment areas within which the four case study aquifers fall. In addition, a common complaint emanating from CAACs is that, being advisory in nature, they have limited influence on decision making; WRMA Regional Offices are not obliged to heed advice tendered by their CAACs, and are not accountable to the CAACs for their actions.

Source: Mumma *et al*., 2011.

At a lower level of the small aquifer or micro-catchment, community groups or more formal water user associations can manage groundwater resources, usually in conjunction with other parts of the hydrological cycle, including surface flows, groundwater recharge, diversions and abstractions, and consumptive water use. However, these organizations and the institutional arrangements associated with them usually focus on the more easily managed parts of the cycle, particularly surface water diversions and consumptive use, and much less on groundwater resource management issues like recharge, prevention of pollution, and aquifer management.

There have been attempts by governments to promote water user associations specifically for groundwater or for groundwater within an IWRM approach, but these are generally in the pilot phase (see Box 29).

Box 29. In Kenya, water resource user associations may have the potential to participate in local aquifer management

As a first step towards formalizing participation in groundwater management, the Water Act in Kenya provides for water users, organized as WRUAs, to participate in water resources management. It envisages that where the water resource in question is a groundwater resource, the WRUA would be formed in regard to the management of that particular groundwater resource. No distinction is drawn between groundwater and surface water resources.

For example, around the Lake Naivasha area, 12 WRUAs in the Naivasha Basin have been established and have:
- Conducted abstraction surveys (both surface and groundwater) and water permit compliance surveys (again for both resources)
- Monitored and checked flow meter status (for both)
- Sensitized water users on water use regulations and their obligations (for both)
- Provided direct feedback to the WRMA on applications for water permits (for both)
- Provided a forum through which water conflicts can be resolved.

Partly as a result of the WRUAs, new rules have been developed that propose both catchment and groundwater protection (The Lake Naivasha Catchment Area Protection and Groundwater Conservation Area Rules), and under which the Lake Naivasha Catchment Area Water Allocation Plan was gazetted in 2011. At present, the powers of the WRUAs are limited to what is allowed under existing legislation. Under the proposed rules, they are expected to be key in education, checking water use compliance, and in promoting water use efficiency.

These rules have yet to be passed into law. This is the first time a Groundwater Conservation Area has been proposed under water legislation since before independence, and may show the way forward for participatory groundwater resources management in Kenya.

Source: Mumma *et al*., 2011.

Participatory approaches risk reflecting existing inequalities

One of the key problems with participation is who gets to participate?

Through decades of experience with participatory approaches, it has become clear that 'empowering' local people in development may shift the balance in decision-making to the local level but at the same time it risks strengthening existing patterns of power and wealth. This is a particular risk with groundwater management where the 'law of capture' has in many areas assigned rights in an erstwhile common resource to those with the power and the wealth to drill wells and appropriate it. Put simply, the larger the surface area and the more financial capital a person has, the more groundwater that person now 'owns' – and this share can be increased further by pumping out from deeper and at a faster rate than others.

The more powerful may either dominate participatory deliberations – or not participate at all.

This consolidation of unequal distribution has two implications for participation. First, the voice of the 'haves' may predominate in participatory processes (see Box 30). Second, the 'haves' may not be so interested to take part in collective management arrangements which give equal voice to smaller interests, or to stakeholders who do not actually own a share of the resource (see the next point).

Box 30. The powerful and the educated may dominate participatory water management processes

The Kenya Water Act provides for the general public to participate in water resources management decisions, particularly as regards water use (i.e. abstraction, etc.) by lodging objections and comments when an application for a water use is made. These mechanisms are designed to enable the public generally and interested stakeholders, particularly the WRUAs to be involved in decision making. The key weakness of these mechanisms is that they depend on pro-activity, knowledge, time and resources by members of the public, and have tended to be used largely by powerful or professional persons rather than members of the public *per se*.

In Morocco, during the development of their regional water master plan, the two river basin agencies of the aquifers analysed in the case study involved the majority of stakeholders in the consultation process. Commissions were set up for this purpose, and the master plan was put out for discussion before being submitting for approval to the National Council for Water and Climate (CSEC). However, there are deficiencies in the consultation process due to the lack of local associations representing all the groundwater users at aquifer level.

In South Africa, public participation processes during development of the proposal to set up a Catchment Management Agency were conducted in several water management areas. South Africa is also working to convert top-down Irrigation Boards into participatory Water User Associations. However, the process is protracted, and one of the reason is the difficulty in meeting race, gender and sector representation quotas for stakeholder participation and for constitution of management committees (a requirement by the Department of Water Affairs). The reality is that there have been very few female farmers and very few previously disadvantaged individuals with water use entitlements.

A further aspect of this asymmetry of power is that most people in any area do not 'own' any groundwater, but they are nevertheless stakeholders.

The groundwater resource is in principle a common asset for the community – the livelihoods of landless labourers or herders may depend on groundwater, drinking water sources require protection of groundwater quantity and quality, access by women to groundwater is a vital part of household management and family health. The interests of the majority in any community may not be properly represented by a 'user association' that comprises only well owners. This was recognized in South Africa (Box 30), but requirements that user associations comprise women and the marginalized prove very hard to implement.

Social dynamics can be barriers to participation

A number of social barriers exist which can significantly limit the active participation of certain societal members.

Common social barriers relate to gender, ethnicity and caste and can extend from interactions at local to national, and even international, level. At the local level, minority groups may be excluded from participating in decision-making and accessing facilities whilst at higher levels individuals may experience discrimination such as being overlooked for positions within institutions. Such barriers make it difficult to achieve inclusive and integrated social development. Identification of stakeholders and understanding of the complexity of their relationships are crucial, but even if provision for inclusion is written in to the process, there can be great difficulty in implementing them (see again the case of South Africa in Box 30).

Some physical aquifer characteristics constrain participation

Firstly, user participation is complicated by the physical invisibility of groundwater systems.

This may make it difficult for users to visualize trends in changes in quantity or quality of groundwater and their implications for use. This proved to be problematic in most of the case study scenarios. UNESCO (Mar 2012) recommends popularizing groundwater information and system behavioural dynamics to users to help make the invisible visible.

Secondly, evidence from the case studies, particularly India, indicates that some hydrogeological settings – fewer stakeholders, or easier to understand resource dynamics – are more conducive than others for engaging communities in groundwater management.

Studies in India show that where there are fewer stakeholders and the resource is better understood, stakeholders are better able to cooperate on groundwater management. Farming communities in hard-rock aquifer areas that implemented rainwater harvesting and aquifer recharge quickly saw a change in water levels in their wells. Conversely, in large alluvial aquifers with high transmissivities, this kind of palpable change was not apparent to users. Shah (2010) observes: "This has created a strange paradox in India's groundwater scene. Large pockets of arid alluvial aquifer areas—Punjab, western Uttar Pradesh, Haryana, western Rajasthan and North Gujarat have excellent aquifers with large storage; yet these are the areas where farming communities depend on 'competitive deepening' of their wells to chase declining groundwater levels. In many hard rock areas with intensive groundwater development for irrigation, farming communities have, over the past four decades, moved from unfettered private exploitation of groundwater to recognizing the shared nature of the aquifer space and thence to groundwater adaptive management of water resources at local watershed level." This suggests that willingness to engage in collective management is likely to be greater in management areas where fewer stakeholders are involved and where the benefits of groundwater management can be measured and felt.

<u>Incentives to stakeholders to participate vary according to the perception of whether there is a problem or not</u>
Where there is no track record of water scarcity, stakeholders may not see the point of cooperating.

Favourable water resource situations in the past may also be an impeding factor for participation. Groundwater users do not feel the need to develop strong co-operative arrangements until their resources are clearly under threat. Kahkonen (1999) finds that in relation to water supply, the relative degree of water scarcity in a community affects the returns to, and emergence of, collective action. Households in communities with relatively scarce water supply have the highest expected returns and thus the strongest incentives to act collectively, while households with absolute scarcity or abundant water supply have low expected returns to collective action and thus weak incentives to cooperate.

…but crisis may change attitudes, or patterns of stakeholder participation may be built during the development phase.

Crises may be able to change the existing negative equilibrium and promote new urgency and create new constituencies for reform. To anticipate this situation, formal or informal user groups can be created during the groundwater development phase with different objectives such as advice on irrigated crop management for farmers, maintenance of pumps and boreholes, discussion on allocation and price of water supply.

<u>The challenge of 'third party' stakeholders and of 'externalities'</u>
Factoring in polluters and others affecting the resource, yet who are not direct users.

There may be third parties who contribute to degradation of groundwater resources (i.e. through pollution or reduction of recharge) but are not direct users. Such stakeholders may benefit from polluting the resources (by not implementing preventative measures or by denuding the catchment and reducing infiltration capacity), but they have little incentive to redress their actions as they do not benefit from the resource itself. Inequity may be exacerbated if the benefits derived by those stakeholders negatively influence other users. In the case studies, examples of private benefit derived at the expense of others were evident, and mutually acceptable arrangements between users and polluters need to be found to help moderate behaviour and promote action in the local public interest.

<u>Challenges in mobilizing support for long-term participation</u>
Participatory approaches can take more time and cost more, and they require long-term commitment from both public services and from communities.

Involving all relevant stakeholders is challenging, particularly due to its consumption of time and other resources (AMCOW, 2012). Despite the principle of user participation being included in national strategies and legal frameworks, participation of groundwater users in decision-making processes is still in its infancy in the case study countries. Changing institutional mandates takes time and building participation requires specific capacity. <u>India</u> and <u>South Africa</u> have made some progress, but the challenge of initially mobilizing support is compounded by the persistent challenge of maintaining long-term participation and interest in the management of a resource. Whilst the case studies and literature demonstrate examples of short-term enthusiasm, particularly when stakeholders rally around a project with external inputs, the maintenance of consistent government support and stakeholder engagement in participatory processes often remains elusive. Incentivizing stakeholders to remain engaged long-term requires ownership and a clear, functional framework where rewards are visible and achievable.

6.4 The Way Forward

Enhancing participation by building on social capital with a specific attention to equity

Costs are less and outcomes better where participatory approaches build on existing social capital.

Social capital is the internal social and cultural coherence of society, the norms and values that govern interactions among people and the institutions in which they are embedded (Kahkonen, 1999). Generally, if social capital already exists, this reduces the cost in time and effort of mobilizing stakeholders for participatory approaches (Brondizio *et al.,* 2009). Box 31 below provides an illustration of this, drawn from Morocco. The existence of social capital through formal and/or informal ties, including non-water related community networks and associations, promote collective action and coordination within a community (Kahkonen 1999). In relation to the management of common-pool resources, Ostrom (2001) lists several attributes of users and communities that facilitate engagement, including “trust and reciprocity” or “prior organizational experience” (see Annex 2).

Box 31. Social capital provides a basis for participation in Morocco, leading to better outcomes

Social capital is one of the five capital assets recognized as a basis for development (together with human, natural, financial, and physical capital, Carney, 1998). The accumulated body of evidence demonstrating social capital’s importance to development potential makes its identification and measurement important. Whilst its measurement is difficult and can utilize a combination of qualitative, comparative and quantitative methodologies (Woolcock & Narayan, 2000), levels of trust, civic engagement, and community involvement can be used as general proxies (WB, nd).

In Morocco, the comparison between groundwater irrigator communities in two over-abstracted areas provides an interesting illustration of the difference in cooperation potential due to social capital. In the Souss Massa aquifer area, there was scant cooperation amongst farmers and many small farmers were forced to sell their land because of unequal financial capital to invest in deep drilling and in water-saving localized irrigation, the small size of certain plots of land, but also differing access to drilling permits (Houdret, 2006).

In the Tadla aquifer area, farmers access groundwater through informal local arrangements and share the water. These arrangements allow the survival of thousands of small farm holdings (Ammar Boudjellal et al., 2011). Building on the existing cooperation, social scientists used role-playing games to identify common interests and develop collective strategies in the Tadla aquifer area (Houdret, 2006).

Intervention designs for participation should be adapted to the existing levels of social capital.

‘Creating’ groups or patterning behaviours through project interventions is a notoriously risky business, basically because institutions set up at government behest and with incentives attached tend to focus on garnering subsidies and to fade away at project end (Gugerty & Kremer, 2000; Grootaert & van Bastelaer, 2001). But where social capital already exists it can provide a first class platform on which to build. Hence, an operational understanding of social and institutional fabrics needs to be gained (Grootaert, 2001; Collier, 1998).

Principles of equity and social fairness demand that the voices of the less powerful should also be heard.

Participation design in programs should be attentive to the needs and unique requirements of minority groups (REC, 1999; Renn *et al.,* 1995; Lebel *et al.,* 2009a). For example, in South Africa, stakeholder participation is a crucial and integral part the water sector reform. To ensure stakeholder participation, a well-designed and elaborate process was adopted for the development of water related policies and legislation (Box 32).

There is still a long way to go, for example on gender inclusion. Whilst the 2012 Africa IWRM report (AMCOW, 2012) reported implementation of gender activities in over half of the countries, only one country (out of 40) reported full implementation of gender mainstreaming in water resources management and development (see

Figure 5). Additionally, the Africa Water Vision 2025 recommended greater engagement with the burgeoning youth population. Clearly, greater engagement with women and youth, in particular, is critical.

Box 32. Consulting South Africa's diverse population about the country's National Water Resources Strategy

As a result of the diverse nature of the South African population, and because water means different things to different people, several different approaches and methods were used to consult about the National Water Resource Strategy (NWRS).

In order to reach all the stakeholders, information on the Strategy was presented verbally, visually and in writing at national level sectoral workshops and public consultation meetings/ open houses held in each of the Water Management Areas (WMAs), throughout the country. A total of 29 national level sectoral workshops and public consultation meetings/ open houses were held in different areas within each WMA, with more meetings in the larger WMAs. Thousands of issues and comments were gathered during the meetings and in writing and submitted to the Department of Water Affairs and Forestry.

Source: Maharaj and Pietersen, 2005.

Interventions could start in areas with potential for success and where intervention costs are lower, in the expectation of spontaneous replication.

The most 'cost-effective' approach would normally be to start in the water management areas where there is the highest probability of showing success and of spontaneous proliferation of that success, whilst also considering the highest benefit for the cost and effort expended (Nkansa & Chapman, 2006; Perez & Tschinkel, 2003; AusAID, 2000).

Figure 5. Illustration of participatory processes excluding minority groups (Source: World Bank Water & Sanitation Program - WSP, 2012)

…but concern for efficiency should not lead to exclusion of vulnerable but lower potential water management areas nor to the exclusion of the poor or marginal.

Equity would require early interventions also in water management areas that are under stress and where the livelihoods of the poor are vulnerable. In addition, within each water management area, although efficiency would suggest addressing principally the problems of the larger water users, equity demands that the interests of all users, even those not owning a share of the resource, be included. These challenges emphasize the difficulty of involving all relevant stakeholders and balancing their perspectives, whilst still maintaining efficient processes.

Promotion of local collective management can link policy (aimed at sustainability, efficiency, equity) to actual outcomes.

Field experience in a number of projects has developed methodologies which have been successful in improving local collective management initiatives and in linking them to the broader policy and governance structure. Box 33 gives an example developed for the MENA region but which could be adapted and applied in many country situations.

Box 33. One methodology for promoting intermediate and local level participatory governance and so linking policy objectives to actual outcomes

Given the need to link government policy objectives and the governance set-up to actual behaviour of groundwater users, the EMPOWERS (*Euro-Mediterranean Participatory Water Resources Scenarios*) project was initiated in Jordan, Palestine and Egypt.

EMPOWERS adopted a participatory approach to action research in water governance, developed collaboratively by a wide range of civil society and government partners in the MENA region. Its objectives included increasing the influence of stakeholders (particularly the poorest and most marginalized) on the planning and decision-making process for the use and management of water resources; and enhancing vertical and horizontal linkages and information flows between water stakeholders.

EMPOWERS provided for a partnership approach to the six stages in the management cycle: visioning; assessing; strategizing; planning; implementing; and reflecting, with the idea of a cycle reflecting a continuous process of experimentation, adaptation and learning, making identification of local solutions possible.

The EMPOWERS approach provided a framework for specialists to support a stakeholder-driven process, overcoming the weaknesses of approaches that focus entirely on top-down decision making by specialists or bottom-up uninformed decision making.

It focused on the local level, in the belief that water governance can only be sustainable if based on the agreement and involvement of water users, and that the vast majority of day-to-day decisions around the provision of water services are taken at those levels, but that local collective groundwater management needs the support and guidance of public agencies located as close as possible to the area being managed..

Although the guidelines that emerged from EMPOWERS reflected the organizational and governance realities in the MENA region, they could be applied, suitably adapted, to many country situations.

Sources: Moriarty *et al*., 2007; WBI, 2009b.

A step-by-step approach is normally indicated, with entry point activities designed to bring visible benefits.

Changing pumping or water use behaviour may bring pain before it brings gain. Interventions may therefore require entry-point activities[26] (EPA) to offset perceived sacrifices by local stakeholders in the broader public interest. It is better, however, to avoid inducements in the form of subsidies as these are not sustainable and behaviours may revert when the subsidy ends. Instead, entry point activities could comprise improvements that need to be done anyway but which may bring quick benefits, such as agronomic or irrigation improvements that can rapidly bring 'more income for less drop'. Such changes in cropping patterns and irrigation and soil-moisture conservation techniques for improved groundwater management could lead to improved farmer returns to promote their continued participation (World Bank, Apr 2009) (see Box 34).

[26] Typically applied in watershed development, EPAs are basically meant for gaining a foothold in the community and in the process, earning the goodwill of villagers before embarking on planned activities. They involve building rapport with the community, strengthening and sustaining it throughout the intervention and thereafter (Dixit *et al.*, 2007).

Box 34. In Andhra Pradesh, a program to promote participatory water conservation increased access to water for the poor, and reduced risk and increased incomes for all

The *Andhra Pradesh Drought Adaptation Initiative* (APDAI) was a World Bank-financed project that experimented with rural community adaptation measures in chronically drought-prone and economically vulnerable areas.

A unique pilot initiative of the project involved villagers sharing groundwater by pooling borewells, which brought rewards to both the farmers owning the wells and to those without prior access to them. The pilot aimed to move groundwater out of the individual into a community domain (introducing collective management), whilst also encouraging transition to lower water-consuming crops. A shared pipeline system, which all group members take turns to operate, also led to collective arrangements by borewell owners.

Agreed community regulations and guidelines included:

- No new borewells to be constructed in next 10 years;
- One borewell must be rested every day (for 20% reduction in water/electricity use)
- During drought the land under irrigation should be reduced proportionally
- All shareholders must use water-saving cultivation methods
- Crop plans must be made for the season, with priority to food and fodder crops
- Area under paddy to be reduced, with no paddy cultivation during cool/dry season.

Reductions in groundwater overdraft were achieved in parallel with equal or increased incomes for all scheme participants, which maintained their enthusiasm. Some of the project measures are being mainstreamed into state government schemes. The approach has the potential to benefit many more farming communities, particularly in arid areas.

Sources: World Bank, 2010; World Bank, 2009.

Processes to promote participation

There are many ways to promote participation in groundwater management, and they can be adapted to local situations.

There is a wide range of methods and tools available to support stakeholder participation. A suite of 'interactive learning processes' has been developed that provide a range of flexible learning by doing approaches to developing institutions for collective water management (see Box 35 and Annex 7). For example, water managers, local communities and hydrogeologists can use these methods to collaborate on local water resources planning and to define and support specific groundwater resource management functions (see Table 5).

Box 35. There is a wide range of interactive learning processes available to promote participatory management

A list of interactive learning techniques derived from Huntjens *et al*. (2011b) and UNEP (nd) is provided in Annex 7. The choice of interactive learning method/s will vary depending on circumstances and objectives, and include backcasting, brainstorming, case studies, focus groups, foresight, group model building multi-stakeholder dialogue, nominal group technique, reframing, or role playing games.

For example, role playing is a type of game in which the participants assume the roles of characters and collaboratively create stories. Participants determine the actions of their characters based on their characterization, and the actions succeed or fail according to a formal system of rules and guidelines. Role playing games can be linked to group model building. In this type of application, models can be represented in terms of role playing games wherein the participants are not simply observing the model from the outside, but actually embedded in the game as actors making decisions about management.

In contrast to the traditional methods of training, the foundation of interactive training is the principle of multilateral communication, characterized by a minimal focus on the point of view of the educator. Instead, training methods focus on the organization of the process of effective communication, in which the participants of the process of interaction are more mobile, more open and active (UNEP, nd).

The suitability of a specific method will depend on its characteristics – e.g. the expertise and facilities needed, the intensity of interaction that it allows and the level of formality – and on the demands of the process at a given time – e.g. objectives and intended level of participation, background of the stakeholders and the available budget and expertise (Huntjens *et al.,* 2011b).

Local communities everywhere have developed ways of monitoring and managing groundwater collectively that are adapted to the local situation.

For example, Table 6 lists (in decreasing order of visibility) twenty groundwater management activities that could be monitored, and therefore 'controlled' by collective decision. Table 6 then lists (in increasing order of difficulty), corresponding techniques that local collective management groups in Yemen have employed to monitor – and regulate – groundwater in their own micro-catchments or local aquifers. The interest of Table 6 is essentially <u>simplicity</u>:

- It lists groundwater management activities that are visible and therefore can be monitored
- It lists corresponding very simple management measures that a community concerned about their dwindling water resource could easily decide upon.

In actual practice, all of the highly visible activities have been the subject of 'management measures' decided by Yemeni communities, along with many of the moderately visible ones.

As part of this study, a simple checklist of 'readiness' was prepared to test whether the conditions for effective collective management of groundwater are in place.

The doyenne of analysts of collective action in relation to common pool resources, Nobel Prize-winning Elinor Ostrom, has argued, along with many others, that local collective management approaches are best able to deal with common pool resources like groundwater. The basic logic proposed is that groundwater users can recognize the problems of depletion, quality deterioration etc. and will have the incentive to work together if cooperation promises significant benefits – in terms of access, sustainability or efficiency. Based on prior research and on analytical work done specifically for this report, ten criteria have been identified (Table 7) for judging how appropriate local collective management may be for any groundwater situation – and how well it is likely to succeed.

<u>Generally, it is not a question of 'either/or' – both top-down rules and public services ***and*** bottom-up local collective management are needed for effective groundwater management</u>

A key challenge for policy-makers is how best to integrate important 'bottom-up' processes of learning with 'top-down' high-level policy strategies and visions. A number of countries (for example the Netherlands, Czech Republic, Hungary, South Africa, Australia, and Thailand) are experimenting with institutional innovation in water resources management to find a balance between processes of bottom-up participation, decentralization and central coordination. Water governance regimes where these processes are more balanced seem to be characterized by a higher adaptive capacity (Huntjens *et al.*, 2011a).

Despite the need to shift the balance of governance towards the local level and more participatory approaches, there will always be the need for a certain degree of top-down governance, for example in the areas of policy, basic rules, knowledge management and cross-fertilization of experiences, transboundary issues, capacity building, setting of standards and conflict resolution.

Even where bottom-up governance or decentralization are working, the state still needs to play an active role in groundwater governance. It can support mobilization of people in local processes, aid in neutralizing local power asymmetry, provide funds for local initiatives, provide technical and professional services to help local capacity building, guarantee quality standards, invest in larger infrastructure, coordinate in externalities that span more than one local administration, facilitate learning processes, and collaborate with local stakeholders for the enforcement of law (Bardhan, 2002).

Table 6. Monitoring and managing groundwater: visibility and implications for local management and public interventions

Water management activities	How can the activity be monitored?	What management measures are possible?
Highly visible activities		
1. Drilling new wells	Presence of drilling rig	Moratorium on new wells
2.Deepening or replacing existing wells	Presence of drilling rig, irrigation activity	Local agreement on maximum depths, moratorium on deepening
3. Spacing of wells	Presence of drilling rig	Employment of traditional well spacing rules (e.g. 500 meters apart)
4. Selling water to tankers	Presence of tankers	Forbidding sales outside the area, or forbidding sales for e.g. *qat*
5. Abstraction for domestic water	Simple observation, as domestic water is hauled by people or donkeys. Piped use can be metered	Local regulation to protect sources Ban on use of domestic water for irrigation
6. Crop type	Simple observation of crops in the field	Ban bananas, alfalfa, or other crops with high water demand
7. Crop area	Simple observation of cropped area	Limits on expansion
8. Conveyance	Simple observation of water conveyance from source to field	Requirement to install lined canals or pipes
9. Distribution	Simple observation of irrigation techniques in-field	Flood, furrow, basin, sprinkler, bubbler, drip
Moderately visible activities		
10. Duration of irrigation	Observation of pumps in operation	Local agreement to limit pumping (hours, seasons)
11. Fuel consumption	Observation of purchase and consumption of liters of diesel	Local agreement to limit diesel use (as proxy for pumping)
12. Excess irrigation	Observation of excess water, weeds	Local agreement to improve water use efficiency
13. Providing water to neighbours	Observation of pipes, water flows, tankers	Local bans could be imposed
14. Depth to water table	Measurement in wells of meters from surface	Target depths could be established
15. Well recovery rate	Measurement of hours to restore level	
16. Aquifer recharge	Measurement of changes in the water table and well yields	Terracing, check dams, basins
Low visibility activities		
17. Quantity abstracted	Metering of m^3, or pumping hours	Agreement on quotas
18. Impact on other wells and springs	Drying up nearby wells or springs, cone of depression	
19. Aquifer transmissivity	Can assess from local experience, Can analyse lateral flow, meters per unit of time technically	
20. Aquifer storage capacity	Can assess from local experience, Can analyse m^3 of water per m^3 technically	

Source: Adapted from a table originally prepared by Bryan Bruns.

Table 7. Ten criteria and ten questions to assess readiness and capacity for collective management

Criterion	Key question
1. Adequately defined boundaries of the resource	Do stakeholders have enough knowledge to be able to relate actions to results?
2. Agreement on access	Do stakeholders agree on who may access the resource and how?
3. Fair distribution of risks, benefits and costs	Are 'big' well owners prepared to cooperate with decisions
4. Collective choice	Are all key stakeholders empowered to take part in decisions?
5. Monitoring and reporting	Do stakeholders have confidence in the measurement and reporting on compliance with decisions and on results
6. Graduated sanctions	Can stakeholders use appropriate sanctions to compel compliance?
7. Conflict resolution	Do all stakeholders agree on a mechanism for adjudicating disputes?
8. Recognition of the group	Is there any external challenge to the stakeholders' right to organize and operate?
9. Adaptive capacity and flexible processes	Can stakeholders adapt in the light of experience or changed circumstances?
10. Links to other governance systems	(*where the aquifer is larger or more dynamic*) Can stakeholders fit in with other governance systems for the same resource (another association, a federating structure, a basin agency…)?

Source: Annex 2.

Note: the first question looks almost the hardest, but in most cases local people will have enough information to be able to define a working concept. And even hydrogeologists are challenged on the 'boundary' question.

7. The Way Forward: Towards Improved Groundwater Governance

Chapters 4 to 6 have assessed the state and prospects of groundwater governance, looking at the functions of governance, at the impediments to good governance, and at options for overcoming these impediments.

The present chapter starts (7.1) by illustrating two country cases where groundwater is an important resource and where governance reforms have been implemented in an attempt to improve outcomes in line with the nation's policies. These reform programs have encountered considerable problems in implementation, and the outcomes are below expectations. The successes and weaknesses, both in the initial reforms and in the way in which they have been implemented, provide lessons for other countries facing similar problems and planning governance reforms. Further information on the country cases is provided in Annex 8.

On the basis of this implementation experience, the second part of this chapter (7.2) – the final section in the report – summarizes all the lessons and options discussed throughout the analysis and suggests how to select governance options appropriate to each situation, and how these options may best be operationalized.

7.1 Reforms in Groundwater Governance: Lessons from Spain and Jordan

Spain

In Spain, groundwater is an important water source, providing about one-fifth of total irrigation water. Historically, groundwater was a private and unregulated resource but problems of over-development and competitive over-abstraction led government to initiate major reforms.

In the 1985 Water Law:

- Well owners were required to register their wells and a nation-wide well inventory and register was to be drawn up
- River basin authorities were to manage and regulate groundwater as part of overall integrated water resources management (IWRM)
- Over-exploited aquifers were to be the subject of a special, more intense, regulatory regime
- Users were to participate through groundwater users associations'

These reforms were clearly in line with best practice. However, the reforms proved unpopular in some regions (see the Guadiana River Basin case) and the measures have been widely disregarded.

- Many wells have not been registered and unlicensed wells have proliferated – the 'official' number of wells is 500,000, but estimates of the actual number ranges up to 2 million
- Under-funding has prevented the newly-created river basin authorities from compiling a full well inventory and so from completing an assessment of the groundwater resource
- The river basin authorities have been unable to enforce the regulatory regime, partly from lack of budget and staff and partly because of widespread resistance to compliance
- Subsidies to commercial irrigated agriculture have driven increased abstractions and accelerated groundwater depletion

The gap between expectations and results is considerable, and the experience may provide some lessons of value outside Spain. The causes of the problems and possible related lessons include:

<u>The reforms were implemented without adequate prior consultation</u> and in consequence were not accepted by the most important stakeholders

  - ➢ However arduous, a national consultation process inclusive of all stakeholders is the best way to shape a reform program that will have widespread stakeholder adhesion

<u>Water resources policy and agricultural policy were not aligned</u>. Whilst water resources policy was to push for sustainable management of the groundwater resource, agricultural policy subsidized expansion of agriculture and agricultural water use, so driving unsustainable levels of groundwater abstraction

- ➢ The policy making process for water resources is best developed in dialogue with agencies responsible for water using sectors, and the resulting policies for water-related activities (agriculture, urban development, regional planning, industrial development, etc.) must be aligned

Although the reform followed the best practice principle of subsidiarity, basin level management of groundwater exploitation has clashed with interest groups at the basin and local levels who see the activities of the river basin authorities as very politicized, bringing the river basin authorities into continual conflict situations

- ➢ Where governance reforms have important regional and local implications, development of the reforms and their implementation need to be conducted with scope for continual dialogue with regional and local stakeholders

Well owners and water users did not buy into participation in collective management and the groundwater users associations have not functioned because well owners do not have trust in the governance system of which they form part. Well owners also seek financial support from the government as an inducement to implement changes.

- ➢ In addition to up-front debate on the shape of the reform program, implementation needs to be accompanied by a continuous communication campaign and by support to aspects of the program that bring gain as well as pain (see Chapter 6 on 'entry point activities')

The river basin authorities lacked the human and financial resources to do the job assigned to them

- ➢ Governance systems need to be adapted to implementation capacity, and adequate provision for financing and capacity building of implementing agencies is essential

Jordan

In the Jordanian highlands, farmers use groundwater for agriculture, but this has led to depletion and to the drying up of springs and oases, including the world-renowned *Ramsar Convention* Azraq Oasis. At the same time, the highland cities are very short of water and are pumping from the Jordan Valley up over 2,000 m in elevation and for considerable distances. The average annual abstraction from renewable aquifers exceeds recharge – at present abstractions are 160% of average recharge, with consequent depletion of reserves and decline in the water table. In addition, fresh fossil water from the non-renewable reservoir in Disi-Mudawwara is used for municipal and industrial purposes in the city of Aqaba and for agricultural purposes. Future use of this aquifer is earmarked for municipal purposes for the city of Amman.

To relieve the problem of depletion and to test ways of transferring groundwater from relatively lower value agricultural uses to higher value municipal and industrial uses, the 1997 Jordan Water Strategy proposed a new policy, and most of the measures were further included in the 2008-2022 Jordan's water strategy:

- Comprehensive groundwater basin management plans were to be prepared for each aquifer
- All wells were to be registered and metered
- Abstraction quotas were to be established for each well as specified in a permit
- Resource charges were introduced for abstractions in excess of the quota
- Groundwater user associations were to be established to collaborate on management measures and to facilitate partnerships with the authorities
- Priority of allocation of groundwater was to be given to municipal and industrial uses, to educational institutes and to tourism. Regarding the agriculture sector, priority was to be given to the sustainability of existing irrigated agriculture where high capital investment had been made. In particular, trees irrigated from groundwater were to receive a maintenance quota, on condition that farmers used advanced irrigation methods.

Results to date

Information on groundwater has improved. The number of monitoring wells has increased to more than one hundred, and monitoring includes both quantity and quality of groundwater. The automation of the network is under study. Groundwater balance and uses are calculated. In addition, exploration of deep groundwater resources has started.

Registration and metering of wells have been successfully achieved but systematic control remains difficult. Most of the wells are equipped with water meters (up to 97% of the licensed wells in 2010) and violating wells are filled in. However, controls are handled by a small number of employees of the Water Authority of Jordan, who have inadequate resources to carry out their tasks fully. In addition, meters are still unprotected and likely to be broken or tampered with. As the meter is paid for by the farmer, the risks of deterioration are reduced but, on the other hand, tampering is quite easy and could become increasingly widespread.

Collective management of groundwater is still not effective. A legal framework has been established for water users associations and pilot projects are implementing this approach for surface water irrigation management. In the Jordan Valley, water user associations now cover about 40% of farmers. However, participation of groundwater users in management has not been reported.

The price mechanism is doing little to restrain demand. Farmers receive limited signals from the incentive structure about saving water. Many farmers are small users and do not pay water fees as their consumption falls within the quota of 150,000 m^3/year per well. These farmers represent the majority of well owners - 72% of the wells in the Amman-Zarqa and Yarmouk basins – so the price of water is having little impact on abstraction. One possibility that has been raised is to scale down the quota to 100,000 m^3/year per well, which would bring down the proportion of non-paying farmers to 53% in this area. For 'larger' farmers, the current price of irrigation water does not seem to be a limiting factor, except those growing on the most marginal land. Venot and Molle (2008) argue that prices are unlikely to enable regulation of groundwater abstraction and significant reduction will only be achieved through policies that reduce the number of wells in use, such as buying out of wells.

7.2 Selecting and Operationalizing Options to Improve Groundwater Governance

Despite the magnitude of the challenges and problems, groundwater governance has not been much on the agenda of decision-makers. Groundwater has failed to feature prominently in water policy dialogue at local, national or global level and as a result its governance has not kept pace with increasing demands and technological advances.
The aim of this report has been to help to put groundwater and its governance at the top of the agenda for decision makers and practitioners by answering the questions:

- Why has groundwater governance failed to stop the emergence of very serious threats to the resource?
- What are the impediments to improving groundwater governance?
- What are the options to overcome those impediments?

This final section in the report summarizes all the lessons and options discussed throughout the analysis, and suggests how to select governance options appropriate to each situation, and how these options may best be operationalized. The section follows the framework used for analysis throughout the report, which distinguished three parts to the groundwater governance system:

- the policy level, where a nation sets its objectives for groundwater
- strategic level governance, where a nation puts in place institutions and instruments to align stakeholder behaviour and actual outcomes with policy objectives
- local level governance, comprising the organizations and institutions which control actual outcomes on the ground, and which respond in varying degrees to rules and incentives

The governance challenge
Groundwater is particularly challenging for governance, because millions of well owners have appropriated it, and they respond more to powerful economic incentives than to the rules governance would impose.

Groundwater is a common resource, but one where people have established *de facto* individual rights which they exploit, driven by strong economic incentives and competing with each other to extract as much as possible as quickly as possible and with no inherent incentives to aim for any sustainability. Governance is further challenged by the fact that groundwater is part of the hydrological cycle, but an unseen part where even specialists are hard pressed to describe the resource and its interactions sufficiently to plan for and manage it.

Governance has to be adapted to the context and to capacity, and be tailored to the size and nature of the problem as well as to the objective targeted.

The challenge is increased by the local specificity of groundwater, each area with its own physical, geographical and socio-economic characteristics. Governance also has to adapt to the state of development and to the problems that past assertion of rights and abstraction behaviour have produced. In some cases the problem is over-abstraction and depletion, in others water needed by fast growing towns is 'locked in' to lower yielding agricultural uses, in others the challenge may be compromised quality or recharge. In most cases, the problems will be more than one of these.

- All these contextual features need to be taken into account in assessing governance options, which have to be adapted to the context and to capacity, and appropriate to the problem to be solved and to the policy objectives targeted.

Governance at the policy level

Setting good policy and handling political economy factors

Policy makers have little incentive to strengthen groundwater governance, so that the large gap between stated policy and what is actually happening is unsurprising.

Although most national policies will be targeting sustainability, equity and efficiency, there is everywhere a gap between stated policy and what actually happens. Policy makers have short horizons and inadequate information, and they are reluctant to put forward policies that constrain the profitability of groundwater use as this affects powerful constituencies – and often the poor, as well. Policy makers prefer high profile surface water investments to the long and politically costly struggle to re-impose order on a largely ungoverned groundwater sector.

- Champions of change need to choose their fights carefully, identifying the really critical issues, and to prepare and present options persuasively

- Options should, as far as possible, reconcile the incentives of decision-makers and stakeholders with some approximation of good groundwater policy

- As a first step, get the budget and the go-ahead for essential resource assessments and for setting up a reliable monitoring and reporting system

Governance at the strategic level

IWRM and cross-sectoral harmonization

Groundwater is the 'poor relation' in water resources management…

Although most countries have adopted policies and have set up organizations for integrated water resource management (IWRM), groundwater struggles for its place in integrated water planning, and governments often fail to provide for the capacity and budgets needed for implementing the groundwater parts of these plans.

…and is often over-ridden by economic interests, particularly agriculture

Groundwater suffers, too, from weak coordination of policy and plans, and good groundwater management intentions are very often over-ridden by powerful interests, particularly from agriculture which is, almost everywhere, the main user.

- Integrate groundwater into water resource planning and implementation, and provide adequate budgets and staff for groundwater within sector agencies
- Align instruments and harmonize sector policies, particularly with the policies of heavy water-using sectors like agriculture
- Strengthen horizontal and vertical coordination, working towards the kind of 'multi-level governance' for groundwater that is emerging in some areas – for example, in China's Hai basin.

Developing and applying governance approaches

The analytical framework in Chapter 2 distinguished three governance approaches, some or all of which are found in most countries:

- A rights and regulation approach awards (or recognizes) legal water rights to users and then checks through a regulatory system that users are respecting the terms of the award.
- An incentives-based approach uses positive and negative incentives – typically incentives that affect the profitability of water use - to bring pumping behaviour at the well head into line with policy.
- A subsidiarity approach delegates responsibility for groundwater management to the local level, usually to stakeholder interest groups.

Rights and regulation governance approaches

Rights and regulatory approaches are very demanding to implement and are usually resisted by stakeholders.

Rights and regulatory approaches are the most precise instruments for matching behaviour at the well-head to society's goals, but are usually impeded by massive institutional and operational problems. Everywhere, rights and regulation approaches have run into problems of defining, issuing and regulating quantified rights. Where these systems have been applied, they have run into big problems of organizational capacity and have usually received scant compliance from well owners. Also, like many systems that essentially recognize past appropriations of the commons, they tend to confirm inequitable patterns of resource ownership.

- Adopting a rights and regulatory approach requires a realistic up-front assessment of the feasibility, especially of the cost and benefits compared to those from an incentives or subsidiarity approach.
- For bigger and formal sector users, rights and regulation approaches are more feasible and can be the best approach. They can also raise much needed revenues to finance groundwater management.
- Combinations of approaches may be possible, for example registering just the bigger, more formal users (who can also be obliged to pay for the privilege), whilst adopting a subsidiarity approach to smaller users.
- Care will always be needed to protect the rights of the smaller against the bigger.

Using the incentive structure

It is easy, even for weak government, to adjust the incentive structure and this can be an essential component – for example, phasing out energy subsidies, which often drive groundwater depletion – but adjustments are politically difficult and can have negative or unintended consequences.

Positive and negative incentives are very powerful determinants of behaviour and, in the case of groundwater, governments are usually able to adjust incentives easily, so they represent attractive mechanisms, especially in a poor country with limited administrative capacity. Table 8 indicates the pros and cons of different options:

- Adjusting input prices like energy or output prices like farm produce are very powerful signals, as agriculture is normally far and away the biggest user. In particular, phasing out energy subsidies would be the quickest way of reducing overdraft in many situations. Attention is needed to knock-on consequences (for example, rise in the cost of transport and in consumer prices generally), to mobilising political constituencies, and to protecting the poor.
- Subsidies to encourage specific behaviours are a more targeted way of affecting outcomes, but they are expensive and open to corruption.
- Bans on crops or irrigation methods are direct and relatively easy to implement, but may run counter to economic efficiency.
- Where transfer of water e.g. from agriculture to M&I is needed, market-based transfers of groundwater can be considered. Attention is needed, however, to economic efficiency and to equity impacts within the aquifer.

Subsidiarity – delegating to local governance structures

'Delegating' to local governance structures can produce good results.

In principle, subsidiarity – delegating management to the lowest possible level – is attractive as it comes closest to the actual decision-makers, the millions of individuals drilling and operating the wells. In some cases, collective management approaches at the local level have demonstrated good outcomes, often in partnership between stakeholders and local public agencies or projects.

- An enabling framework for encouraging 'subsidiarity' should be in place.

Table 8. The pros and cons of options for changing pumping behaviour through the incentive structure

Options for adjusting incentives	Pros	Cons
Adjusting input prices influenced by government e.g. energy, fertilizer, seeds etc.	Within government power Easy to administer Immediate and universal impact May generate fiscal revenue	Affects all sectors using the input (especially energy) Puts up consumer process Reduces farm incomes May produce unintended effects[27] May be inequitable (e.g. loss of employment)
Adjusting output prices influenced by government e.g. trade controls, cropping pattern controls, crop bans, taxes, official procurement prices		
Subsidizing specific behaviours such as more efficient irrigation (drip, greenhouses etc.)	Can increase farmers' incomes whilst reducing water use (more income per less drop) Positive impact on GDP	Can be hard to administer Can be expensive Open to inequity and corruption Does not necessarily reduce water use (Jevons paradox)[28]
Bans on specific irrigation techniques	May be easy to implement (e.g. ban on center pivot) May resolve a large part of the problem quickly	May be hard to implement (e.g. banning flood irrigation) Direct impact on the value of farmer assets and incomes
Facilitating regulated water markets	Allows transfer to higher value uses Profit incentive to comply Relatively easy to regulate	Limited to wells near settlements High cost of transporting the water May be inequitable

Table 9. Governance approaches to groundwater, with the requirements of each and when they might be the most indicated

Requirements	Which approach may be the most effective?		
	Rights and regulation	Incentive structure	Subsidiarity
Is there a legal framework of rights and regulatory instruments that is adapted to the situation and which is implementable? If yes…	✓		
Is there a pattern of groundwater users complying with authority? If yes…	✓		
Is the approach administratively simple and low cost?	x	✓	✓
Is there strong social capital and/or a history of agreed water rights and collective management at the local level? If yes…		✓	✓
Is inter-sectoral water transfer an objective? If yes…	✓	✓	
Is there a serious depletion problem? If yes…			✓
Is there a serious pollution or recharge problem? If yes…	✓		✓

Choosing amongst governance approaches

A mix of approaches will normally be indicated- and flexibility, adaptation, and an eye on equity are needed.

Overall, there is no one right approach to governance. In each context, one or more of the three approaches may be better, as Table 9 shows.

[27] For example, raising diesel prices in Yemen led to conversion of farms from growing grapes and cereals to production of the soft drug *qat*, as this was the crop that returned the highest income per drop

[28] Jevons paradox is that if the use of an input is made more efficient, using it is more profitable, so *more* of it will get used

- Flexibility, piloting initiatives and learning and adapting as needed are likely to be good stances.
- Particularly important is to adapt approaches to implementation capacity.
- In all approaches, it is essential to keep an eye on equity considerations, as there are powerful incentives pushing towards resource capture by the more powerful.

Information, knowledge and communications

Information, knowledge and communications functions are essential components of good groundwater governance.

Without information, groundwater is very hard to manage. Without communications, compliance with a governance framework is unlikely.

Information on groundwater is, in most countries, a very weak spot.

This is due to high costs of collection, to prevalent capacity and skill gaps, and to lack of commitment and resources from policy makers. Information is needed not only on aquifer characteristics but on uses and users, in order to understand behaviour and trajectories. Once collected, information has to be available to managers and to all stakeholders through an open information policy.

- It is important to persuade governments to invest in information and knowledge
- Lower cost ways of gathering information should be tried - through stakeholder participation or using remote sensing or other new technologies.
- Increased attention is needed to getting to know uses and users, and to understanding motives and the incentives local people face.
- It would be useful to set up monitoring and reporting on the outcomes and impacts of policy and on the performance of the governance system, so that findings can feed back into intelligent adjustments.

Communications with stakeholders is the key to developing governance systems that have the buy-in of stakeholders.

Very importantly, transparency, dialogue and interactive communications and learning are key to strengthening stakeholder ownership of governance, and to improving compliance and thereby outcomes.

- Promote transparency, dialogue and interactive communications and learning as a key component of groundwater governance

Conflict and conflict resolution

Hitherto rare, conflict over groundwater is becoming more frequent.

Because groundwater extracted by tubewell was a new and abundant resource, the early stages of the groundwater revolution saw little conflict and, because of the nature of groundwater, conflict has typically been much less than in the case of surface water. However, there are many potential sources of conflict now emerging due to over-abstraction, pollution, or changes of land use, and well owners are often in conflict with public agencies, for example over regulation.

Depletion, competition and the impacts of climate change are intensifying the scope for groundwater conflict.

Conflicts are nowadays tending to intensify and become more frequent as the resource becomes fully developed, especially as development in many areas has produced a pattern of inequitable access to groundwater. On top of this, climate change is introducing costs and risks that are hard to manage, including increased demand for groundwater and reduced recharge, with consequent heightened risk of conflict. Disputes have also started to emerge between states over transboundary aquifers.

Dispute resolution mechanisms are being set up, and old ones are adapting – but with mixed results.

Traditional dispute resolution mechanisms have difficulty in adapting to the tubewell, but some are showing 'adaptive capacity'. A few modern dispute resolution mechanisms are also being set up, sometimes alongside the old, but with mixed results.

- Good governance capable of flexible and adaptive responses is the best way to solve disputes – even before they start
- Dispute resolution mechanisms may be modern or traditional, centralized or local – the key criterion is that they be accepted as fair by all parties.
- For transboundary aquifers, ways to avoid or resolve disputes can be developed based on the positive experience in various river basin initiatives.

The role of participation and local collective management in good groundwater governance

Empirical evidence suggests that participation and local collective management can be effective approaches to good water governance.

Participation appears to be effective in improving outcomes because it increases stakeholder ownership and because stakeholders often have access to information and can devise solutions better than or complementary to those delivered from the top-down. Perhaps the most important aspect of participation is that it can align objectives of government with those of local people, so giving local stakeholders incentives to good groundwater management, and can empower local stakeholders in subsequent implementation by giving them influence over outcomes. Local collective management is also more likely to take account of the needs of future generations

In addition, participatory approaches, which empower local people by giving them influence over outcomes, may improve sustainability.

If a well owner is convinced that changing pumping behaviour will slow or halt resource depletion, he or she may well collaborate in collective groundwater management, taking account of the needs of his or her children.

There is a range of participatory approaches to groundwater management, from 'consultation' to fully delegated groundwater management.

The more 'bottom-up' the approach, the stronger the participation and empowerment of local stakeholders. Clearly the level of participation will depend on the local context, with the need for skilled support increasing as participation moves towards local collective self-management. In all this, it is salutary to recall that in practice local stakeholders are already managing most of the world's groundwater. In this sense, participation could be seen as much as levels of participation by government agencies in local governance arrangements as *vice versa*.

Despite this potential there are many impediments to participation and local collective management.

Frequently, the legal and institutional provisions do not empower collective management institutions. For example, water user associations may be 'consulted' over basin plans, but they rarely have any power to participate in decisions. At the local level, there is usually much more experience in collective management of surface water, and stakeholders are often very slow to adapt to the quite different demands of groundwater.

There is a risk that participatory approaches may reflect existing inequalities.

The more powerful may either dominate participatory deliberations – or not participate at all. A further aspect of this asymmetry of power is that most people in any area do not 'own' any groundwater, but they are nevertheless stakeholders. Ways to include and empower these people are often hard to negotiate, especially when there are social or cultural barriers. An equally challenging 'inclusion' issue is how to get the participation of those who are not directly benefitting from the resource but who may be polluting or hampering recharge.

As groundwater problems intensify, incentives to participation and collective management grow.

User participation is complicated by the physical invisibility of groundwater systems, which make it harder to agree on the problems and on the responses and which make monitoring more difficult. In fact, unless people agree there is a problem – where water scarcity is not yet apparent, for example – stakeholders may not see the point of cooperating. However, crisis and the threat of climate change may change attitudes. Overall, combinations of social and physical conditions are likely to determine whether people cooperate. For example, settings where stakeholders are fewer and resource dynamics are easier to understand are more conducive.

Partnerships between local stakeholders and public agencies are an effective approach, but this requires long term commitment – on both sides.

Most successful collective groundwater management has not been done by local people alone, but in partnership with a public agency, which can provide knowledge, capacity building etc. However, engaging in participatory approaches is costly and requires long-term commitment from both public services and from communities.

Experience shows some do's and don'ts

- Costs are less and outcomes better where participatory approaches build on existing social capital, and so interventions should be adapted to the existing levels of social capital.
- Principles of equity and social fairness demand that the voices of the less powerful should also be heard, and this is something which public agencies can push for.
- Prioritization in so vast a field is important, and so interventions could start in areas with potential for success (see Box 36) and where intervention costs are lower, in the expectation of spontaneous replication.
- Concern for efficiency should not lead to exclusion of vulnerable but lower potential water management areas, nor to the exclusion of the poor or marginal.
- A step-by-step approach is normally indicated, with entry point activities designed to bring visible benefits.
- Experience around the world has developed a number of approaches and tools, and these can be adapted and replicated, with mutual learning, as many communities will have better ideas than those of the public agency.
- Finally, in general it is not a question of 'either/or' – both top-down rules and public services **and** bottom-up local collective management are needed for effective groundwater management.

Box 36. Determining when collective management is more likely to work – and getting started

- Where fewer stakeholders are involved
- Where the benefits of management can be measured and felt
- When there is a perception that there is a problem, perhaps driven by a 'critical moment'
- Where social capital already exists that is appropriate to the task (e.g. equitable, pro-poor) and is adaptable and capable of adopting innovations
- Where there is community solidarity, especially when it is inclusive of women and the marginalized
- When there is relatively less inequity in resource ownership or access to resources

Getting started

- Start early before the problems become too great
- Go step-by-step in a sequence, with M&E (monitoring and evaluation) and adjustment built in
- Balance equity with efficiency
- Factor in externalities

There are many ways to get collective management to work.

The most persuasive argument in favour of collective management is the success of some partnerships between public agencies and local people. Box 37 describes a successful approach at low cost that has already brought benefits not only of sustainability but also of increased incomes to two-thirds of a million people.

Box 37. Andhra Pradesh Farmer Management Groundwater Systems Project (APFAMGS) shows that farmers can reduce groundwater use and still earn higher incomes

Several programs in India have supported community groundwater management. The most substantial project in terms of geographical coverage and methodology is the *Andhra Pradesh Farmer Management Groundwater Systems Project* (APFAMGS).

In APFAMGS there was no investment in infrastructure. The emphasis was instead on increasing the collective understanding of the groundwater resource. Farmer measurement of basic hydrological parameters was to be the basis for coordinated crop planning by groundwater-dependent farmers. APFAMGS is active in 62 hydrological units (sub-basins), spread over seven districts in Andhra Pradesh. The average population size of a hydrological unit is about 10,000 people and the average number of direct groundwater users in a hydrological unit is 400. The total population benefitting from the program was about two-thirds of a million people.

In each of the hydrological units a number of **activities** are undertaken:

- Promoting participatory hydrological monitoring – with farmers measuring their own water levels as well as running local rainfall stations
- Crop water budgeting for the entire hydrological unit on the basis of available recharge – with farmers in the end deciding themselves how to adjust their cropping system
- Farmer water schools, again largely run by farmers – to improve understanding of groundwater, introduce water saving techniques and change cropping patterns.

The **impact** of the APFAMGS activities has been analysed from the detailed database that the project maintained. In more than half of the hydrological units with predicted negative water balances, farmers adjusted their crop choice reducing the proportion of high water demand crops. In particular, water-intensive rice cultivation was reduced or even eliminated.

There has also been a significant increase in the use of improved field irrigation, moisture conservation and micro-irrigation methods– going up from 15 % of the area in 2005/2006 to 34 % of the area in 2007/2008. The increase concerns methods that involve both subsidized investment – in particular drip and sprinkler systems, and also methods that concerned unsubsidized management measures adopted by farmers, such as check basins or the use of vermicompost.

As a result, water tables have risen, and - most importantly - better groundwater management did not result in lower returns – but rather the opposite. The net value of agricultural outputs in all the hydrological units in the project was higher than in the pre-project period – with increases ranging from 6% to over 100%. In non-project areas on the other hand, the net value per hectare dropped by up to half as groundwater availability dwindled.

The **lessons** are:

- Knowledge and awareness are key to persuading farmers that they can manage groundwater more sustainably
- There are many ways to reduce groundwater use, some requiring investment (and perhaps subsidy), some of them simply requiring farmer knowledge and effort
- With careful management, farmers can reduce groundwater use and earn higher incomes

Sources: Taher *et al,* 2011; van Steenbergen, 2010.

Getting started towards improved groundwater governance

This section – and the whole report – contains a perhaps bewildering set of issues and recommended actions. But every journey starts with the first steps. The following is a list of entry point activities on how to initiate help to countries to improve groundwater governance. Of course, not all these activities are applicable everywhere, but a brief menu is as follows:

- **Engage with the policy makers** to understand their concerns and constraints. Go outside the water ministry to seek harmonization and support from agriculture, planning, finance, municipal development. Carry out economic analysis of key issues and present it persuasively. Recruit champions and try to come up with win-win agendas. Link governance reform to investment, if relevant.

- **Agree with policy makers on investment in groundwater knowledge**, and offer technical and financial support if needed. Focus not only on resources but on uses and users, identify hot spots. Draw on the results to persuade policy makers of the need for action. Link the results to an analysis of governance needs (see below).

- **Help government to chart a reform path towards better groundwater governance**. Assess the needs and constraints to good governance, following the methodologies in this report. Identify what approaches are best indicated (rules and regulation; incentives; subsidiarity) and work out a reform path over time, and an actions and investment plan.

- **Help build strong groundwater organizations/departments/agencies** to ensure groundwater's place in IWRM planning and to strengthen their support to the governance approaches chosen. Match their capacity to the tasks decided upon. Dialogue with government to ensure that the organizations are adequately resourced with skills and budgets.

- **Identify the scope for collective management, and devise ways to support it.** Work at the project and local level, in tandem with agriculture colleagues and those involved in decentralization or local level government.

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Annexes

Annex 1. Comparison between surface water and groundwater characteristics

Characteristic	Surface water	Groundwater
Visibility	Resource immediately apparent	Resource not apparent
Accessibility	Largely restricted to riparian lands	Accessible to all overlying lands
Volume	Small volumes (rivers) but most potentially available	Large volumes but top fraction most available
Quality	Highly variable	Generally of good quality although some groundwater is highly saline; can also contain natural contaminants such as arsenic and fluoride
Evaporation	Small-moderate losses for rivers; high for reservoirs	Negligible losses
Residence times	Short (days to weeks to months)	Long (months to years to centuries)
Investment	Low-high cost of equipment and infrastructure; private and public investment	Relatively low cost of equipment; usually private investment
Cost of pumping	Relatively cheap to pump per m^3.	Pumping costs vary considerably with deep aquifers requiring lifts of hundreds of metres.

Annex 2. Governance & political economy

The relevance of governance and political economy to good groundwater outcomes

Governance is defined by UNDP (2000) as "the system of values, policies and institutions by which a society manages its economic, political and social affairs through interactions within and among the State, civil society and the private sector" and relates to the broad social system of governing. Understanding governance allows us to match a nation's policy objectives with the mechanisms for translating those objectives into actual outcomes.

Empirical evidence demonstrates strong causal relationship from good governance to better development outcomes (Cotlear, 2009). Governance assessments have traditionally focused on formal governance structures and processes, and less on the interactions between actors or institutions. In recent years, however, governance analysis has looked more at the way these formal structures actually work, taking into account the underlying political economy drivers and with an emphasis on power relations, incentives, formal and informal processes (UNDP *et al.,* 2009).

Political economy refers to the way the political environment and the economic system influence each other. It is concerned with "the distribution of power and wealth between different groups and individuals, the processes that create, sustain and transform these relationships over time" (Collinson 2003). It has become widely accepted that understanding the political economy context of reforms is useful from a diagnostic perspective in order to be able to assist countries effectively in designing and implementing development strategies and policies (World Bank 2009a). The approach followed in the present report includes political economy analysis as part of the governance analysis.

Water governance is defined by GWP (2012) as "the political, social, economic and administrative systems that are in place, and which directly or indirectly affect the use, development and management of water resources and the delivery of water service delivery at different levels of society" (Rogers and Hall, 2003). As a subset of the above, groundwater governance is thus concerned with the enabling conditions – policies, the planning function, the framework of laws, rights and regulations, the incentive framework, and the organizations set up to implement these things – for developing and managing groundwater resources in a socially responsible, environmentally sustainable and economically efficient manner.

Theoretical background: why groundwater, as a common pool resource, may pose particular governance challenges

Common pool resources like groundwater require specific governance arrangements if objectives of sustainability, efficiency and equity are to be attained

Common pool resources are those where there are few barriers to access but where abstraction by one user diminishes the pool available to others (examples include fisheries, forests, pastures or water). Hardin (1968) proposed that common pool resources face overuse and ultimate destruction because individual users have no incentive to curtail their use of the resource. Anyone preserving it for future use simply leaves it for others to use. In addition, over-abstraction often imposes costs on third parties through, for example, subsidence of overlying lands, changes in water quality and loss of groundwater dependent ecosystems. The only solutions, he claimed, were for either government control or privatization of the resource so that users had an incentive for sustainability. Ostrom et al (1999) have pointed out that collective management of common pool resources is an alternative approach that has been successful historically. It can avoid some of the shortcomings with government control, such as excessive overhead costs and lack of management capacity, and some of the problems of privatization such as inequitable access to the resource.

Groundwater is an extreme case of a common pool resource because it is very easy to 'individualize' it simply by tapping it under one's own land, and there is inherent tension between this individualization and the interests of the general run of users.

Groundwater and the social system that depends on the groundwater resources (household, community, economic sectors, rules and institutions) are in mutual interaction and these interactions are very complex (Andeies *et al*., 2004; Walker *et al.,* 2006; Berkes *et al.,* 2003). Because of this complexity, simple models of governance and behaviour are of limited value and research suggests changing the focus from seeking optimal states and the determinants of maximum sustainable yield, to analysing system resilience, with a focus on adaptive resource management and adaptive governance (Walter, 2004). The bottom line is that a multidisciplinary approach including social science is key to understanding and improving groundwater governance.

How does the theory on common-pool resources and socio-ecological systems apply to groundwater?

Groundwater users have incentives to find solutions to local issues when coordination yields substantial benefits. As Schlager (2007) points out, "owners of closely situated wells, for instance, may readily realize the effect that their pumping has on one another as water levels in their wells decline under heavy pumping and begin to recover as they reduce their abstractions". In this case, "ability of resource users to monitor resource stocks" and "well-understood dynamics of the resource" are observed and can provide a basis for two key characteristics for successful cooperation. Users may be willing to rely on spatial or temporal restriction on the use of the resources. Unfortunately, information on groundwater budget is often lacking, difficult to collect and to analyse (World Bank 2009). Defining aquifer boundaries, structure or capacity of the 'invisible resource' requires assistance from engineers and hydrologists. Also, groundwater users themselves cannot easily determine the number of other pumpers, how much water they are taking, the effects of their pumping on the overall productivity of the groundwater basin, etc. Tackling appropriation problems for groundwater is therefore not always easy.

Ross and Martinez-Santos (2007) examined the relevance of the design principles proposed by Ostrom and others for sustainable groundwater management and governance within the context of a comparison of groundwater irrigation management in Australia and Spain. These examples share some favourable features for internal self-management including well defined resource boundaries and long term resource tenure. Other aspects are more problematic including agreement on sustainable resource yields, users' involvement in setting resource management rules, and users' capacity to establish their own resource management arrangements including effective monitoring and sanctions. A further challenge identified by these authors is to establish incentives for collaboration that link user benefits with their contribution to the water management regime.

Lastly, Ostrom's design principles for sustaining long-enduring, common pool resource systems on a local scale and those for establishing or sustaining a governance system to deal with the challenges and uncertainties related to complex, cross-boundary groundwater systems may be expected to be distinct for several reasons (e.g. Healey *et al.*, 2003; Rotmans, 2005; Grin, 2006). First, complexity is substantially increased since larger-scale water resources usually must be managed across different time-frames and at different scales (local, regional, national and international). Second, and in contrast to traditional planning for infrastructure, governments and stakeholders at all levels need to be flexible under changing conditions when determining groundwater policies and measures. This is especially the case when considering the uncertain impacts of climate change (Hallegatte, 2009) and socio-economic developments on groundwater systems. Third, knowledge about the effectiveness of alternative interventions is incomplete and knowledge that exists, and is important to management, is often dispersed amongst several different stakeholders (Huntjens, *et al.*, 2012)

For dealing with complexities and uncertainties related to groundwater governance and climate change adaptation additional or adjusted institutional design propositions are necessary that facilitate learning processes. This is especially the case for dealing with complex, cross-boundary and large-scale resource systems, such as the groundwater systems in Morocco, Kenya, Tanzania, South-Africa and India, which are the country case studies being analysed in this report. We provide a set of ten refined and extended institutional design propositions for groundwater governance and climate change adaptation (see Table A2-1), based on the works from Ostrom (1993 and 2005) and Huntjens *et al.* (2012). Together they capture structural, agency and learning dimensions of the governance challenge and they provide a strong initial framework to explore key institutional issues in groundwater governance. These institutional design propositions support a "management as learning" approach to dealing with complexity and uncertainty. They do not specify blueprints, but encourage groundwater governance tuned to the specific features of local geography, ecology, economies and cultures. The report, especially in chapter 5, highlights some of the principles and suggests ways to implement them.

Table A2-1: Ten institutional design propositions for complex (ground) water governance systems and climate change adaptation (based on Ostrom, 1993 and 2005 and Huntjens et al., 2012)

Institutional Design Proposition	Explanation
1) Clearly defined boundaries	Defining the boundaries of the resource system and of those authorized to use it can be thought of as a first step in organizing for collective action (Ostrom, 1993). When confronted with social and physical challenges, e.g. the impacts of climate change on groundwater, it is important to clarify who is affected by this problem and who has the responsibility, capacities, access to resources and information to deal with this problem (Huntjens *et al*., 2012).
2) Equal and fair (re-distribution of risks, benefits and costs)	Those who receive the highest proportion of the water also pay approximately the corresponding share of the fees (Ostrom, 1993). Within the context of climate change, or other external disturbances, it is important that stakeholders at risk are given opportunities to participate in reshaping and reducing the risks to which they are projected to be exposed. This requires engagement with, and strong representation of, groups likely to be highly affected or especially vulnerable (Huntjens *et al*., 2012).
3) Collective choice arrangements	Most individuals affected by operational rules can participate in modifying them (Ostrom, 2005). In large-scale resource systems it is important to enhance the participation of those involved in making key decisions about the system, e.g. on how to adapt to climate change (Huntjens *et al*., 2012).
4) Monitoring and evaluation	Monitors who actively audit CPR conditions and appropriator behaviour are accountable to the appropriator and/or are the appropriator themselves (Ostrom, 1993). Additionally, it is also important to monitor and evaluate decision-making and the development and implementation of policies (Huntjens *et al*., 2012). An important measure is to have agencies at least review impacts of their policies and other interventions (Huntjens *et al.*, 2012). The process of monitoring and evaluation serves to adjust the course of action and motivate those driving the processes. Actions and objectives can then be adjusted based on reliable feedback from the monitoring programmes and improved understanding (Nyberg, 1999).
5) Graduated sanctions	Appropriators who violate rules are likely to receive graduated sanctions (depending on the seriousness and context of the offense) from other appropriators, from officials accountable to these appropriators, or from both (Ostrom, 1993).
6) Conflict prevention & resolution mechanisms	Appropriators and their official have rapid access to low-cost, local arenas to resolve conflicts among appropriators or between appropriators and official (Ostrom, 1993). In complex water governance systems we can also observe a number of conflict prevention mechanisms, such as timing and careful sequencing, transparency, trust-building, and sharing of (or clarifying)responsibilities (Huntjens *et al.*, 2012).
7) Minimal recognition of rights to organize	The rights of appropriators to devise their own institutions are not challenged by external governmental authorities (Ostrom, 1993).
8) Nested enterprises / polycentric governance	When common-pool resources are larger and more dynamic, as in the case of (transboundary) river basins or groundwater systems, and involve multiple stakeholders, an additional design principle tends to characterize robust systems, viz. the presence of governance activities organized in multiple layers of nested enterprises (Ostrom, 2005). Nested enterprises are functional units to overcome the weakness of relying on either just large-scale or only small-scale units to govern complex resources systems.
9) Robust and flexible processes	Institutions and policy processes that continue to work satisfactorily when confronted with social and physical challenges but which at the same time are capable of changing (Huntjens, et al., 2012). Building trust and reciprocity are important elements of a robust and flexible process (Huntjens *et al.*, 2012). Robustness of a water governance system may be enhanced by cross-sectoral policy integration or mainstreaming climate adaptation, because it reduces the incidence of large adverse side-effects and feedbacks or 'maladaptation' (Dovers & Hezri, 2010).
10) Policy learning	Policy and institutional adjustments based on commitment to dealing with uncertainties, deliberating alternatives and reframing problems and solutions (Huntjens *et al*., 2012).

Annex 3. Analysing groundwater governance

A bespoke theoretical framework was synthesized from the literature as a basis for analysis and for the identification of governance gaps and possible ways forward. Analysis drew examples from both the literature as well as a detailed review of the governance arrangements of five case study countries to understand the main issues and bottlenecks for groundwater improvement. The synthesized theoretical governance analysis framework and the more applied approach to the case studies, capturing issues across both strategic and local levels, are presented.

Dimensions of groundwater governance

This section summarizes essential dimensions that need to be addressed to analyse water governance capacities and related challenges. The framework presented below is a hybrid of different frameworks developed by Huntjens (2011), Huntjens *et al* (2010, 2011a, 2012), Pahl-Wostl & Lebel (2010) and the OECD report on Water Governance in OECD countries (2011). For the purposes of the analysis in this ESW report a distinction is made between context, water governance capacities and performance as presented in the figure below.

The socio-economic, political and cultural contexts for water governance vary greatly among places and countries, for example, with respect to histories of settlement, ethnicities, class and gender relations. Hence, the context in which a water governance system is embedded has a strong influence on the system and its performance. As a result, institutional reforms may lead to quite different outcomes as a consequence of the context. To move away from simplistic panaceas context variables need to be taken into account (Ostrom *et al.*, 2007; Harrison, 2006; Pahl-Wostl, 2009; Pahl-Wostl & Lebel, 2010).

The six elements presented above are not mutually exclusive, and there might be cross-cutting issues and interdependencies. For example, sectoral fragmentation of water-related tasks across ministries and agencies is considered a policy gap, legal gap and institutional gap, albeit from a different perspective and/or different indicators.

Important to note is that the analytical framework is being used as a heuristic device in this report, in order to identify and highlight predominant governance issues based on the case-study reports. This means that not each and every variable of the framework will be covered and/or described in full detail in Chapter 4 and 5, but only the ones that stand out according to the empirical analyses.

This report doesn't attempt to fully evaluate the performance of different modes of governance, although this has been put forward by many authors as a key focal area for future research (Jordan, 2009; Biermann *et al* 2009; Pahl-Wostl, 2009; Huntjens, 2011). Measures for the performance of a groundwater governance system should allow assessing and evaluating the degree of satisfaction with the current state of groundwater governance. Obviously a governance system should achieve its stated goals. Failure of doing so is a clear sign of a non-satisfactory performance without alluding to any normative claims (Pahl-Wostl & Lebel, 2010). In this ESW report performance has not been taken into account in the case-study reports, but it is strongly recommended as a follow-up activity.

Judging performance, or the effectiveness, of a water governance system is challenging for several reasons. First, identification and attribution of specific outcomes is often confounded by other social and political processes that surround the management and governance of water resources. Second, the outcome of management measures is uncertain due to the complexity of the system to be managed and uncertainties in environmental and socio-economic developments influencing the performance of implemented management strategies. It is therefore important to monitor the water governance systems for a longer period and on a frequent basis. Third, the relevance and meaning of indicators for success or failure may be judged differently by different groups, and thus lead to different assessments of the performance of water governance systems (Pahl-Wostl *et al.* 2007). Nevertheless, some approaches are likely to be useful without alluding to any normative claims. One approach is to assess the achievement of stated goals, for example the Millennium Development Goals (related to water resources) or IWRM goals, including economic efficiency, social equity and ecosystem sustainability. Also process criteria are useful for assessing performance, such as access to resources like information, clear task definition, structured decision-making and cost-effectiveness. In governance systems where there is an effort to elicit consideration of alternatives other criteria related to being visionary and deliberative should also be considered (Dore, 2007).

ESW Analytical Framework for Water Governance (developed by P. Huntjens)

Context

Socio-economic political and cultural context and its influence on the water governance system

Policy

- Level of actual implementation of policies
- Level of cohesion and/or level of sectoral fragmentation of water-related tasks across ministries and agencies
- Consideration of possible measures: diversity in physical and management interventions
- Dealing with uncertainties: Reversible and flexible options
- Time horizon: combining short and long term
- Solutions for short term problems do not cause more problems in the (far) future (20 years or more)

Legal and regulatory systems

- Water laws (appropriateness or adequateness)
- Number of conflicting mandates
- Number of conflicting targets / objectives
- Appropriate regulations
- Water rights
- Structural constraints being addressed (e.g. change in the regulatory framework
- Legal provisions concerning access to information, participation in decision-making (e.g. consultation requirements before decision-making)
- Access to courts
- Level of enforcement and compliance
- Effectiveness of regulation

Governance Capacities

Institutional arrangements

- Cross-sectoral cooperation
- Cooperation between administration levels
- Cooperation across administrative boundaries
- Clearly defined boundaries
- Equal and fair (re-)distribution of risks, benefits and costs
- Collective choice arrangements
- Monitoring and evaluation
- Graduated sanctions
- Conflict prevention and resolution mechanisms
- Minimal recognition of rights to organize
- Nested enterprises/polycentric governance
- Robust and flexible planning processes
- Policy learning

Information management and communication

- Joint/participative information production
- Explicit consideration of uncertainty & commitment for dealing with uncertainties
- Monitoring & Evaluation
- Data-sharing: Governments exchange information and data with other governments and/or stakeholders
- Access to information on water resources, expert knowledge and management plans
- Open and shared databases
- Quality and usage of decisions support systems
- Use of scenarios in decision-making
- Interdisciplinarity
- Broad communication
- Utilization of information
- Risk perception by experts and stakeholders

Financing/funding

- Cost recovery mechanisms
- Insurance mechanisms for water related risks
- PPP-financial constructions
- Water pricing (for irrigation, households, industries)
- Payment for ecosystem services
- Polluter pays principle
- Tradable permits related to water abstraction/use
- Cost-benefit analyses (incl. short term - long term) of governance improvement vs inaction
- Cost efficiency of various governance options
- Resources availability
- Allocation of resources
- Water integrity and corruption

Performance

Sustainable water use and development

Achieving IWRM goals:

- Economic efficiency
- Social Equity
- Ecosystem Sustainability

Level of policy learning

Achieving Millennium Development Goals

Participation and capacity building

- Level of, or provisions for, stakeholder participation
- Non-governmental stakeholders actually contribute to agenda setting, analyzing problems, developing solutions and taking decisions ("coproduction")
- Non-governmental stakeholders are involved in decision-making on acceptable risks
- Level of incorporation of local knowledge and experience into management planning
- Level of partnership among actor groups
- Mobilization of broad support for change
- Transparency about decision-making (procedures)
- Governments actively disseminate information and data to the public
- Public awareness programs on water problems
- Water education in school programs and for Professionals
- Technical capacity and economies of scale

In governance systems confronted with disturbances, crises and/or external changes, such as the impacts of climate change and related uncertainties, it is important to assess the level of policy learning (Huntjens *et al.*, 2011). A formal comparative analysis of eight water governance systems in Europe, Africa and Asia has shown that systems with a higher level of policy learning also have more advanced adaptation strategies in place for dealing with the impacts of climate change on water resources (Huntjens *et al*., 2011).

Annex 4. Incentives and tools for groundwater management: description and conditions for application

This annex describes the main instruments used to manage groundwater, with a specific focus on economic instruments. Advantages and disadvantages of each instrument are discussed and illustrated through examples.

Prescription

Description - This strategy consists of prescribing the water quantity (or quality[29]) allocated to each user or to a group of users through quota. Quota can be on volume (and requires a water meter system) or on time (for example for collective irrigation wells for example). Quotas on volume are often determined each year depending on the recharge.

Pros and cons - Quota is one of the main instruments used to manage water demand for irrigation (Molle & Berkoff, 2008) and groundwater over-abstraction (Giordana and Montgimoul, 2006). Reasons of this predominance include transparency, ability to ensure equity, capacity for adjusting to the inter-annual recharge variability, and limited losses of incomes (Molle and Berkoff, 2008). If water supply is short of demand by, say, 30%, quotas consist in reducing every user 's supply by 30%, while regulation through prices consists of raising prices until the least "economically efficient" operators reduce their overall demand by 30% (Molle, 2009).

However, regulation through quotas involves high transaction costs associated with its implementation and enforcement, especially when users consist of millions of scattered borehole owners in the countryside. In addition, quotas foster equity at the cost of efficiency: the government agency doesn't have the information to best allocate the water between users and the system often lacks flexibility in response to changing environment. Quotas may be subject to arbitrariness if their definition is not transparent. Enforcement and control requires strong and credible institutions and few users or a participatory approach for collective quota. Lastly, quota system provides less incentive to change the users' behaviour compared to other instruments (Tiwari and Dinar 2000).

Examples - In Israël, quotas help conserve groundwater. In this country, the Water Commissioner sets quantity and quality standards for those who have the right to receive water (all sectors). Farmers are forbidden to use water in excess of the amount allocated to them, even if they have their own well, and water meters at the well are read and controlled by staff of the Water Commissioner's office. In 1999, after severe depletion of the country's water resources, the Water Commissioner decided on a reduction in the water quotas for agriculture (1998 was set as the basic year for the cut) by a 40% average and in the years 2000 - 2002 an average reduction of 50% was decided on (World Bank 2006). Note that in addition to the quota system, farmers pay their water following an increasing block rate.

In France, individual and collective quotas are used to cope with water scarcity, with an increased participation of users. In the Beauce area, where groundwater was severely depleted after several droughts, the representatives of the irrigator association and the authorities have decided to meet annually and assess the trend of aquifers. During this meeting, they agree on the maximum volume available and the quota is distributed among farmers. Information on well location and installation of water metering is a condition to receive subsidies from the European Union, which helps control the implementation of the decision.

Mexico and Spain also have a quota system, but the impact of this strategy in term on groundwater conservation is uncertain. In Mexico, the government announced the decision to withdraw unused portions of groundwater quotas, which generated a "use-it-or-lose-it" feeling among farmers (Shah, 2007).

Penalty

Two types of penalty will be considered in this annex:

- Groundwater pricing: volumetric tariff, increasing volumetric tariff

[29] Regulatory instruments are also the most common instrument used to address non-point source pollution, but this is not discussed in this note.

- Fees and taxes: tax on production, tax on other inputs (energy, fertilizers, or pesticides), tax per irrigated area, tax that depends on the technologies used and practices, betterment levy (on land).

These types of penalty can be combined in instrument such as the "two part tariff" (volumetric tariff and per ha).

Pricing groundwater - Water pricing is the most commonly used economic instrument for quantitative (ground)water management of domestic and industrial uses. It is also a mean to cover maintenance costs and support water management programs. The level and structure of water price vary between countries and regions, leading to different effectiveness in providing incentives for sustainable water use and different levels of cost recovery (Acteon 2009). Volumetric rates increasing block rates or seasonal rates (peak and off peak prices) are often applied, although decreasing block rates for water supply may also exist (to account for the decrease in marginal cost, but incentive to conserve water is reduced).

Charging for full cost is almost never socially and politically possible. Depending on the standpoint, water price should relate to the marginal cost (economic efficiency), the social opportunity cost (allocative efficiency, which includes present and future uses), or the environmental cost (ecological efficiency). In addition, price should also take into account the farmers' willingness to pay. Reviews of international experiences show that users are never charged the full price of water (Molle, 2009). In practice, price results of a compromise between economic efficiency and social acceptability. In the agricultural sector, the use of (ground)water pricing is mainly oriented toward revenue generation and recovery of administrative cost, rather than toward economic efficiency or incentives for users to change consumption patterns (Tiwari and Dinar, 2001; Molle, 2009). Even in the water supply sector of many developing countries, the utility is charging tariffs that are substantially below the full cost of service (Nauges and Van den Berg, 2006).

Pros and cons - The merits of introducing a price for water are its potential:
- to increase water conservation, especially in the domestic and industrial sectors just after the implementation of the pricing policy: in Canada in 1999,water use was 70% higher when consumers faced flat monthly rates rather than volume-based rates; however once the volumetric rate is in place the demand is rather inelastic
- to increase government revenues and cover (part of) the cost of service and the administrative cost (including monitoring and control);
- to improve the government's knowledge base regarding water use; calculating the full cost of water is also a way to quantify the externalities and inefficiencies in the system, which can be addressed using other instruments.

The main drawbacks include:
- It raises water user's costs, which can result in a lack of equity: poorest users must be protected from an inability to access water due to financial constraints; it is essential that negative incentives be accompanied by positive measures offering attractive alternatives (market opportunities, subsidies for modernization, technical advice, etc.) and exit options with compensation.
- Volumetric pricing is needed to address water conservation issues makes this strategy expensive, especially for an application in the agricultural sector. Often small users who abstract less than a given volume of water are free of charges as the costs of collecting revenue might outweigh potential financial revenues. Remote sensing techniques can be used to calculate groundwater use (Kemper 2007).
- When water pricing is implemented in the irrigation sector, it is generally low and doesn't provide incentive to save water (Molle, 2009); it could be used as a revenue to pay for groundwater programme rather than an incentive to conserve water.

Examples - Balilia *et al*. (2001) used a combination of simulation and optimization techniques to analyse the impacts of irrigation water pricing and agricultural policy scenarios on aquifer conservation in the Hamadan-Bahar plain, Iran. The analysis of the results indicates that water pricing by itself can considerably reduce the agricultural demand for aquifer groundwater.

The best known case of water pricing for agricultural use is Israel where all irrigation diversion and delivery points are metered and closely monitored. The extraction fee reflects the scarcity value of water (not the cost of supply) and comes in addition to the quota system. Other economic incentives have stimulated the use innovative technologies, most obviously in irrigation, but also in manufacturing and urban water use.

In Jordan (El Nasar, 2009), water price has been introduced in 2002 as a demand management tool. Before then, a water permit delivered by the Water Authority specified the maximal volume of abstraction for a well (quota). With the new bylaw, the prices levied depend on the volume extracted annually (free for less than 150,000 m3, increasing block rate for higher volumes). The first year of implementation (2002-2007) showed significant reduction in groundwater over pumping (El Naser, 2009). However, enforcement of metering requirements has not been easy so far, due to technical, financial and administrative constraints. More than a quarter of existing wells are unlicensed and fees from the majority of wells used for agriculture purposes are not collected. When this fee structure was established, the amount of water pumped by some small farmers actually increased to take advantage of the higher free water (USAID 2007). The current price of irrigation water does not seem to be a limiting factor for any farmer, except those growing on the most marginal land. Venot and Molle (2008) argue that substantial increases in volumetric charges would not result in major water savings but would further decrease the income from low-value or extensive crops. A shift towards high value crops would raise water productivity but would also entail a transfer of wealth to the government and to wealthier entrepreneurs. According to these authors, prices are unlikely to enable regulation of groundwater abstraction and significant reduction will only be achieved through policies that reduce the number of wells in use, such as buying out of wells.

In Canada (Nowlan, 2005), six of the thirteen provinces and territories charge for groundwater extraction. Generally, only industrial or commercial users pay fees, and usually only when water usage reaches a relatively high level. Water use measuring is generally imposed as a condition of licences. The social and environmental costs are external. For example, Ontario defines full cost as “The full cost of providing the water services [including] the source protection costs, operating costs, financing costs, renewal and replacement costs, and improvement costs associated with extracting, treating, or distributing water to the public and such other costs as may be specified by regulation.”

California (USA) assesses an annual water right fee to each holder of a permit or licence based on the volume of water in acre-feet (one acre-foot = 1233 cubic metres or 1.2 million litres) authorized for diversion under that water right permit or licence.

Other taxes and fees - The range of taxes or fees that indirectly affects groundwater uses is large, and the choice depends on the policy objective and the targeted users. To limit agricultural groundwater abstraction, taxes (or decrease in subsidies) on energy or on irrigated crops are often proposed to address the issues of lack of information. For non-metered agricultural abstraction, fixed charges per hectare can be used, as for example in the Seine-Normandy river basin district in France (Acteon, 2009). In developed countries, taxes are also used to address diffuse pollution issue. In theory, environmental tax should be based on the Pigouvian concepts of equating marginal benefits with marginal cost can also be used but requires information on both of these aspects, which may be expensive. For industries which consumptions are unknown, a specific coefficient to each type of industry is applied for transforming abstraction into consumption (Acteon, 2009). Current tax and charge level remain very low as compared to the production cost (example from the Netherland, groundwater price accounts for 0.03% of the industry turnover (Ecotec, 2001)).

The “ambient tax” is proposed by economic literature to solve diffuse pollution problems and could be adapted to manage groundwater, when individual withdrawals cannot be observed (Segerson, 1988; Giordana and Montgimoul, 2006). Ambient tax is designed from an observed variable (for example the groundwater level, or pollution level) which is affected by individual but not observable decisions (withdrawals, or non-point source pollution). The collective tax (or subsidies) is applied is the variable is above (or below) a specified target.

Pros and cons - Using tax does not require knowing individual withdrawals. It can influence behaviour in some cases, and it provides financial resources, which can support projects for alternative supply or environmental protection.

However, setting up a tax mechanism requires a high level of information because users’ demand functions and environmental impacts have to be quantified. Moreover, its political acceptability may be quite limited. For example, energy pricing is often an effective means to subsidize rural producers, as for example in India, so the social impact of such increasing energy price should be carefully assessed[30]. Collective taxes breed an implicit unfairness: complying individuals may pay for the gains of others.

Examples - In India, regulation, water pricing or property right reforms are unlikely to reduce groundwater extraction because of the logistical problems of regulating a large number of small, dispersed users. However, electricity supply and pricing policy offers a powerful toolkit for indirect management of both groundwater and energy use.
Taxes on pesticides exist for example in Denmark, Norway, Finland, Sweden, France and Belgium, and reductions in pesticide use have been noticed after the introduction of the taxes, although price elasticity estimates are low (Acteon, 2009).
Ambient taxes have been studied theoretically but rarely applied. In Ethiopia case some field experiments show that the high collective tax is an efficient and relatively reliable mechanism to solve the problem of excess exploitation of an open-access common pool resource (biodiversity conservation) (Reichhuber *et al.,* 2009).

Property rights

Description - The total maximal volume that can be extracted is converted into a number of individual (or collective) rights (also called concessions, permits, licenses, or entitlements), which can be allocated to individual (or collective) users. Usually, property rights are assigned on the basis of traditional rights, resource mobilization patterns and land entitlements. The basic difference between a quota and right allocation is that the former may have various conditionalities, including a predetermined price, and be subject to modifications, based on external conditions and number of users (Tiwari and Dinar, 2000). Right tradability introduces an increase option for allocative efficiency, provided the water right system is well codified (Kemper, 2007)

Pros and cons - Property-right systems are used to ensure an optimum allocation of water within or between sectors. The allocation of ownership to the water users can also increase farmers' willingness to invest in water conserving technologies (Tiwari and Dinar, 2000).

Groundwater rights do not resolve over-exploitation. Experiences show that the level of abstraction rarely decreases. In addition, setting up property rights requires strong institutions to ensure a credible sanctioning system and to protect against the development of potential monopolies. Besides, markets may not be very active if transaction costs are high. Lastly, shifting from quotas (resource owned by the state allocated for a specific use) to tradable water rights may encounter cultural resistance as well as opposition from vested agricultural interests (Molle, 2009).

Examples - Water markets have been established in the US, Australia, Chile, Spain and Mexico.
In Chile, market incentives to promote more efficient water use, particularly within the agricultural sector, have not worked as expected, and irrigation efficiency remains low nationwide (Bauer, 2005). Most of the groundwater user groups in Mexico have not restricted total water use of the aquifer (Kemper, 2007). In the Rio Grande water market (New Mexico), annual and permanent water rights are leased and traded, usually within the same sector. Although it has led to an efficient allocation, the Rio Grande market resulted in little investment in efficient technologies, and total water use has actually increased. Issues of fairness were also raised, as smaller and poorer user organizations and municipalities are disadvantaged (Acteon, 2009).

One of the areas where groundwater abstraction has decrease is Arizona, where total permitted abstraction volume decreases based on assumed changed in technology (Kemper, 2007).

Shah (2008) reports that, out of 431 groundwater basins in California, only 19 are 'actively managed', implying some restrictions on pumping. Active management basins are generally overlain by highly urbanized areas where governments or municipalities can easily buy water rights to serve high paying urban consumers. In all the rest, groundwater management is passive, basically involving federal government grants to build infrastructure to import surface water and supply it to groundwater users in lieu of pumping.

[30] Kemper (2007) suggests lump sum payment for poor farmers rather than subsidies for everyone

Payments

Description - This category includes investments for alternative resources (dam), subsidies to change of behaviour (improved practices for example) to improve equity, or to assist economic transition to a less consuming activity. For example, subsidies of technological improvement (e.g., in the form of tax credits or grants) on water conservation technologies can be paid to the farmers on the basis of per unit water saved or designated types of water saving technologies; this will be efficient in term of water saving only if farmers do not expand their field or increase their cropping cycle (but incentives are great).

Voluntary approaches are increasingly applied especially for limiting diffuse pollution. They include for example contracts on specific agricultural management practices which specify compensation payments to farmers. Competitive payments where users should be proactive can also be used, and allows shifting the information burden to the landowners. As payment value is often difficult to price, voluntary agreement creates a market to value environmental services.

Subsidies to assist economic transition changing from agricultural to non-farm system may include proactive migration and commuting, access to transport and markets, access to social networks, access to credit and financial institutions, or access to education (Moench, 2007).

Financial resources can be provided by the government, by water agency who collect fees on water or pollution or by beneficiaries (who can be a private entity) who pay for environmental services (Salzman, 2005).

Pros and cons - This strategy is often well accepted by groundwater users, and can be a solution when enforcement of other instruments is not possible for political reasons, for example, when reforms may be subject to local, state and national coercion because users (farmers especially) are part of the polity. Payments can accelerate change in behaviour toward sustainable practices. Voluntary agreements provide additional flexibility and can be adapted to local constraints. As noted by Montginoul (2011), these arrangements could be used to manage groundwater if farmers are financially incited to adhere, if society accepts to pay the cost of these arrangements, and if they are only temporary measures, which help farmers to change their behaviour. According to her study, the absence of arrangements organized up to now on groundwater can be explained by: “the difficulty of identifying liabilities and defining what we understand by overexploitation, the absence of water rights and the limited economic interests of an overexploited for which the consequences will appear only after a very long period of time”.

Subsidies or payments should to be implemented only for the transitional period required for making a shift towards the adoption of water saving technologies or practices. Otherwise, there is a risk of over-dependency of farmers on such grants and credits and high potential impacts of elimination of such subsidy on the poor households and rural employment opportunities (Tiwari and Dinar, 2000).

Arguments for payment are controversial as it means paying polluters to reduce their harms. Unable to force the polluting or abstracting source to pay for the costs it imposes, the beneficiaries must instead pay the source to reduce its activities. Some may argue that effective nonpoint source regulation and enforcement would be feasible (Salzman, 2005).

Examples - A classic example of a government paying for improved groundwater management is illustrated with the Pegeia aquifer in the western part of Cyprus. Several measures were undertaken to reverse increasing exploitation trends, and address potential sea water intrusion and pollution risks. First the development of alternative water supply sources for irrigation financed by public authorities reduced drastically the abstraction from farmers. Then financial incentives were proposed to promote technological adjustments aimed at water conservation in the domestic sector[31].

In Morocco, the change in irrigation technology (switch to drip irrigation) is subsidized by the government. Again, this strategy can save water if farmers do not expand their field or increase their cropping cycle.

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[31] INECO Guideline towards the application of institutional and economic instruments for water management in countries of the Mediterranean basin (INECO project).

In Europe, agri-environmental subsidies can be granted famers who stop irrigation on plots located in water scarce regions. This measure is used for instance in the Marais Poitevin region (France) which is suffering from a high water stress. However, only a limited number of contracts have been signed so far. Investigations of farmers showed that the level of the subsidy was not sufficient. In addition, there is high uncertainty on the time period the subsidy will be available (Acteon, 2009).

Only few voluntary agreements on groundwater were find in the literature: Vittel in France is a well described example (Salzman, 2005). In the Boutonne river basin in France, which suffers from important water shortages combined with water quality problems, a drinking water company has been acquiring boreholes from farmers to access good quality groundwater in exchange of financing reservoirs for irrigation (Acteon, 2009).

Annex 5. Assessment of case study aquifers against GW-MATE regulatory and operational governance features

	Governance Feature	India						Kenya				Morocco				South Africa										Tanzania				
		Punjab		Maharashtra		Kerala		Merti	Nairobi	Tiwi	Baricho	Souss-Chtouka		Haouz		Botleng		Steenkoppies		Bapsfontein		Houdenbrak		Dinokana-Lobatse		Makutupora	Babati	Arusha	Dar es Salaam	Kimbiji
		Provision	Capacity	Provision	Capacity	Provision	Capacity					Provision	Capacity	Provision	Capacity	Provision	Capacity	Provision	Capacity	Provision	Capacity	Provision	Capacity	Provision	Capacity					
Regulatory &Institutional	Drilling permits & GW use rights	2	0	3	1	3	1	1	1	1	1	2	1	2	1	2	1	2	2	2	1	1	1	2	1	3	3	3	2	3
	Tools to reduce GW abstraction	2	0	2	1	2	1	0	0	0	0	2	3	2	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1
	Tools to control borehole drilling	2	0	2	1	2	1	0	0	0	0	2	1	2	1	2	1	2	2	0	0	0	0	1	1	0	0	0	0	1
	Sanctions against illegal well operation	2	1	2	1	2	1	0	0	0	0	2	1	2	1	1	1	3	2	0	0	0	0	0	0	0	0	0	0	0
	Land use controls over polluting activities	-	-	-	-	-	-	0	0	0	1	2	1	2	1	1	0	2	1	1	1	0	0	0	0	0	0	0	0	0
	Government institution as resource guardian	1	0	2	1	2	1	1	1	1	1	2	1	2	1	1	1	2	2	1	0	1	1	1	1	0	0	0	0	0
	Community aquifer organizations	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	2	2	0	0	1	1	1	0	1	1	1	1	0
Operational	Public participation in GW-management	2	1	2	1	2	1	1	0	0	0	0	0	0	0	1	1	2	3	1	0	1	1	1	1	1	1	1	1	0
	GW management Action Plans	0	0	2	1	1	0	0	0	0	0	3	2	2	1	3	0	0	2	0	0	1	0	2	1	1	1	1	1	0

0 = Absent; 1 = Weak; 2 = Acceptable with room for improvement; 3 = Satisfactory

Annex 6. Social Accountability Tools

Budget Literacy Campaigns are efforts—usually by civil society, academics, or research institutes—to build citizen and civil society capacity to understand budgets in order to hold government accountable for budget commitments and to influence budget priorities.

Citizen Advisory Boards are groups of volunteers representing different stakeholders at national or at local level that come together with a common aim to help in bettering water provision.

Citizen Charter is a document that informs citizens about the service entitlements they have as users of a public service, the standards they can expect for a service (timeframe and quality), remedies available for non-adherence to standards, and the procedures, costs and charges of a service. The charters entitle users to an explanation (and in some cases compensation) if the standards are not met.

Citizen Report Card is an assessment of public services by the users (citizens) through client feedback surveys. It goes beyond data collection to being an instrument for exacting public accountability through extensive media coverage and civil society advocacy that accompanies the process.

Citizen/User membership in decision-making bodies is a way to ensure accountability by allowing people who can reflect users' interests to sit on committees that make decisions about project activities under implementation (project-level arrangement) or utility boards (sector-level arrangement).

Citizens' Juries are a group of selected members of a community that make recommendations or action proposals to decision-makers after a period of investigation on the matter. Citizens' juries are a deliberative participatory instrument to supplement conventional democratic processes.

Community Contracting is when community groups are contracted for the provision of services, or when community groups contract service providers or the construction of infrastructure.

Community Management is when services are fully managed or owned by service users or communities. Consumers own the service directly (each customer owns a share) when they form cooperatives. Strong bylaws; clear account keeping procedures; payment through banks; regular schedule for meter reading and billing; annual auditing; small operating staff with clear reporting lines to the user committee.

Community Monitoring is a system of measuring, recording, collecting and analysing information, and communicating and acting on that information to improve performance. It holds government institutions accountable, provides ongoing feedback, shares control over M&E, engages in identifying and/or taking corrective actions, and seeks to facilitate dialogue between citizens and project authorities.

Community Oversight is the monitoring of publicly-funded construction projects by citizens, community based and/or civil society organizations participating directly or indirectly in exacting accountability. It applies across all stages of the project cycle, although the focus is on the construction phase.

Community Scorecard is a community-based monitoring tool that assesses services, projects, and government performance by analysing qualitative data obtained through focus group discussions with the community. It uses the 'community' as its unit of analysis monitoring local facilities. It usually includes interface meetings between service providers and users to formulate an action plan to address any identified problems and shortcomings. It solicits user perceptions on quality, efficiency and transparency. Users reveal priorities and score performance of providers in each of those; the inter-face meeting is at the heart of the process.

Grievance Redress Mechanism (or *complaints-handling mechanism*) is a system by which queries or clarifications about the project are responded to, problems with implementation are resolved, and complaints and grievances are addressed efficiently and effectively.

Hybrid Citizen Report Card (CRC) / Community Scorecard (CSC) - Surveys and community score cards. Dialogue for the CSC used the results of the CRC as evidence for the discussion. Two providers to compare results.

Combination of impacts at national and at local level. Both tools complement each other and both revealed significant progress.

Independent Budget Analysis is a process where civil society stakeholders research, explain, monitor and disseminate information about public expenditures and investments to influence the allocation of public funds through the budget.

Information Campaigns are processes to provide citizens with information about government plans, projects, laws, activities, services, etc. A variety of approaches can be used such as public meetings, mass media, printed materials, public performances, and information kiosks.

Input Tracking refers to monitoring the flow of physical assets and service inputs from central to local levels. It is also called input monitoring.

Integrity Pacts are a transparency tool that allows participants and public officials to agree on rules to be applied to a specific procurement. It includes an "honesty pledge" by which involved parties promise not to offer or demand bribes. Bidders agree not to collude in order to obtain the contract; and if they do obtain the contract, they must avoid abusive practices while executing it

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Independent Water Budget Analysis - Independent Budget Analysis refers to analytical and advocacy work by civil society and other independent organization aimed at making public budgets more transparent and at influencing the allocation of public funds through the budget. Once the budget has been formulated and made public, civil society can continue to demand accountability by undertaking independent budget review and analysis (IBA) exercises.

Participatory Budgeting is a process through which citizens participate directly in budget formulation, decision-making, and monitoring of budget execution. It creates a channel for citizens to give voice to their budget priorities.

Participatory Focus Groups and Surveys - NGOs specialized in water can facilitate the implementation of focus groups and surveys to understand user's necessities and demands.

Participatory Physical Audit refers to community members taking part in the physical inspection of project sites, especially when there are not enough professional auditors to inspect all facilities. Citizens measure the quantity and quality of construction materials, infrastructure and facilities.

Participatory Planning convenes a broad base of key stakeholders, on an iterative basis, in order to generate a diagnosis of the existing situation and develop appropriate strategies to solve jointly identified problems. Project components, objectives, and strategies are designed in collaboration with stakeholders.

Procurement Monitoring, in the context of DFGG, refers to independent, third-party monitoring of procurement activities by citizens, communities, or civil society organizations to ensure there are no leakages or violation of procurement rules.

Public Displays of Information refers to the posting of government information, usually about projects or services, in public areas, such as on billboards or in government offices, schools, health centres, community centres, project sites, and other places where communities receive services or discuss government affairs.

Public Expenditure Tracking Systems (PETS) in Water - They track flows of funds from central to local government, and to utilities. They locate and quantify political and bureaucratic capture, leakages, misallocation, etc. It is a quantitative/auditing tool, most useful if planned more than once.

Public Hearings are formal community-level meetings where local officials and citizens have the opportunity to exchange information and opinions on community affairs. Public hearings are often one element in a social audit initiative. The objective is to examine the opinions of everyone regarding critical issues affecting their community.

Public Reporting of Expenditures refers to the public disclosure and dissemination of information about government expenditures to enable citizens to hold government accountable for their expenditures.

Social Audits of Water Sector/Policy - A social audit aims to make public institutions or private entities more accountable for the social objectives they declare. Citizens monitor how resources are used to achieve social objectives; examine cost and finance, but it is not its central concern; it can use surveys and then propose solutions; they assess performance and results.

Study Circles are small groups (diverse, usually 8-12 participants), democratic, peer-led discussions which provide a simple way to involve community members in dialogue and action on important social and political issues. Community-wide study circle programs involve many study circles happening at the same time across a community, provide a basis for problem solving, and lead to action at many levels, create new personal relationships and community networks.

User Management Committees refer to consumer groups taking on long-term management roles to initiate, implement, operate, and maintain services. User management committees are for increasing participation as much as they are for accountability and financial controls.

Users' Representation in Water Regulatory Boards - Representatives from professional association relating to health, engineering, law etc. Members must be user of water. Regulator mediates conflicts.

Water Watch Groups to feed Regulator with users' feedback - Regulators can use organized groups of citizens at regional levels to feed the regulator with decentralized data about water provision. That decentralized voice should be used as feedback for improving.

Sources: GAC, nd; WBI, 2009c.

Annex 7. A model for participatory learning and interactive learning techniques

Strategies for groundwater need to evolve to reflect experience through a 'learning approach'

Adaptive (ground)water management implies a real paradigm shift in (ground)water management from what can be described as a prediction and control to a management as learning approach. Such change aims at increasing the adaptive capacity of groundwater aquifers at different scales. Examples of structural requirements for a water management regime to be adaptive are summarized in Table A7-1. Two different regimes characterized by two different management paradigms – management as control versus management as learning - are contrasted as the extreme, opposing ends of six axes. Depending on the context, bridging the gap between the two paradigms may take time but developing mechanisms for facilitating learning processes in the policy may be a first step.

Table A7-1 - Different regimes and their characteristics (From: Pahl-Wostl et al., 2005)

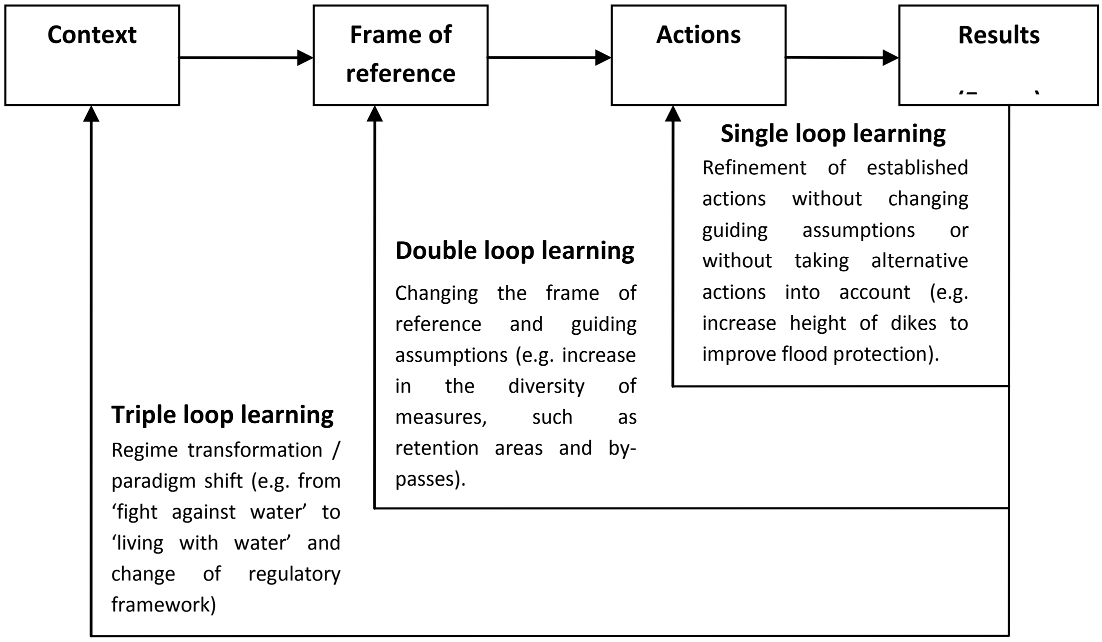
Dimension	Prediction, Control Regime	Integrated, Adaptive Regime
Governance	Centralized, hierarchical, narrow stakeholder participation	Polycentric, horizontal, broad stakeholder participation
Sectoral Integration	Sectors separately analysed resulting in policy conflicts and emergent chronic problems	Cross-sectoral analysis identifies emergent problems and integrates policy implementation
Scale of Analysis and Operation	Transboundary problems emerge when river sub-basins are the exclusive scale of analysis and management	Transboundary issues addressed by multiple scales of analysis and management
Information Management	Understanding fragmented by gaps and lack of integration of information sources that are proprietary	Comprehensive understanding achieved by open, shared information sources that fill gaps and facilitate integration
Infra-structure	Massive, centralized infrastructure, single sources of design, power delivery	Appropriate scale, decentralized, diverse sources of design, power delivery
Finances and Risk	Financial resources concentrated in structural protection (sunk costs)	Financial resources diversified using a broad set of private and public financial instruments

…and adjustment to the legal framework can support this learning approach, for example concerning access to information and enhancing participation in decision-making

Improving legal provisions concerning access to information and participation in decision-making (e.g. consultation requirements before decision-making) may be a first step towards increased policy learning. Increased levels of policy learning lead to more advanced coping strategies in governance systems confronted with social and physical challenges (Huntjens *et al.,* 2011a). Policy learning is defined by Hall (1988) as a 'deliberate attempt to adjust the goals or techniques of policy in the light of the consequences of past policy and new information so as to better attain the ultimate objects of governance'. It is important to take into account that learning takes place at different levels beyond just refining established actions or single-loop learning (Figure 5). Advanced information management and integrated cooperation structures discussed in the sections above are key factors leading towards higher levels of policy learning: advanced information management may be considered the lubricating oil within cooperation structures.

Partnership approaches amongst stakeholders improve this learning process

Developing and sustaining capacity through increased interaction between stakeholders and institutions for example joint field visits or common training session is needed to build up experience to cope with uncertainty and complexity of socio-ecological systems.



Triple loop learning concept derived from Hargrove (2002), and adjusted by Huntjens *et al* (2011a). Reproduced by permission of Robert Hargrove (2011).

Results from empirical analyses show, for example, that centralized political and economic systems, privatization, commercialization of the environment, rigid bureaucratic systems, and political secrecy and poor public access to information can impede social learning. The quality of the interaction, the shared ownership of a task or project, openness for mutual testing and contradiction, and the opportunity for reflexive moments are all important components of such a practice (Pahl-Wostl *et al,* 2007).

A sample of interactive learning techniques...

Backcasting is a method to develop normative scenarios and explore their feasibility and implications. Important in the sustainability arena, it is as a tool with which to connect desirable long term future scenarios to the present situation by means of a participatory process. The method is used in situations where there is a normative objective and fundamentally uncertain future events that influence these objectives. The central question of backcasting: "if we want to attain a certain goal, what actions must be taken to get there?"

Brainstorming is a group creativity technique designed to generate a large number of ideas for the solution of a problem. Many variants available: nominal group technique (often used in GMB), group passing technique, team idea mapping method, electronic brainstorming, directed brainstorming, individual brainstorming, question brainstorming.

Case studies allow you to develop the ability to analyse, ask relevant questions, develop decisions and defend one's point of view; improve participant's communicative skills; develop ability to see situation from several different angles and take into consideration various factors that influence the situation; and develop several decisions and analyse them.

Focus groups are broadly defined as meetings to obtain public understandings on a distinct area of interest in a permissive environment (Morgan, 1997). In a relaxed atmosphere, a group of six to eight people share their ideas and perceptions. Within a smaller group, the participants usually feel that they have a larger influence on the discussion, and it is easier to tempt reticent participants to contribute.

Foresight is a tool for developing visions, understood as possible future states of affairs that actions today can help bring about (or avoid). Foresight is a non-deterministic, participatory and multidisciplinary approach. It can be envisaged as a triangle combining "Thinking the Future", "Debating the Future" and "Shaping the Future".

Group Model Building is a method for facilitating 'deep involvement' of a group of individuals in the building of a model of a particular management system, in order to improve group understanding about that system, its problems and possible solutions, which will directly or indirectly lead to better management decisions (Hare, 2003). When using such a method, the model itself is not the product of the process; the product is the generation of common understanding among model builders during the process.

Multi-Stakeholder Dialogue aims to bring relevant stakeholders or those who have a 'stake' in a given issue or decision, into contact with one another. The key objective of an MSD is to enhance levels of trust between the different actors, to share information and institutional knowledge, and to generate solutions and relevant good practices. The process takes the view that all stakeholders have relevant experience, knowledge and information that ultimately will inform and improve the quality of the decision-making process as well as any actions that (may) result. With sufficient time, resources and preparation, an MSD can be a very effective tool for bringing diverse constituencies together to build consensus around complex, multifaceted and in some cases, divisive issues.

Nominal Group Technique is used to structure group work aimed at gaining consensus on priority setting and/or highlighting topics of importance in the management system (Delbecq *et al.*, 1975). To overcome the problems of domination and marginalization of the group members, the technique begins with a round-robin collection of participants ideas about a subject in private. This enables all participants' view to be collected fairly. Each participant's ideas are then presented for critical appraisal and discussion by the group in a facilitated group workshop. The ideas are then ranked in this workshop by the group using some form of voting/ranking system. The highest ranked idea is then set as the idea of highest priority and importance to the group. This technique is good for getting groups to prioritize ideas belonging to a single theme, however, it does not work well for multiple themes and if quick decisions are required (Hare, 2003).

Reframing is an intervention stimulating participants to go beyond their own frame of reference and to approach a problem or relation from a different perspective. It is possible to use such intervention when processes are stagnated on content and/or social relationships.

Role Playing Game (RPG) is a type of game in which the participants assume the roles of characters and collaboratively create stories (Waskul & Lust, 2004). Participants determine the actions of their characters based on their characterization, and the actions succeed or fail according to a formal system of rules and guidelines. Role playing games can be linked to group model building. In this type of application, models can be represented in terms of role playing games wherein the participants are not simply observing the model from the outside, but actually embedded in the game as actors making decisions about management.

Sources: http://www.unep.org/IEACP/iea/training/guide/default.aspx?id=1193; Adapted from Merri Weinger, Teacher's guide on basic environmental health.

Annex 8. Groundwater management and governance in Spain and Jordan

Spain

In Spain, approximately 75 percent of groundwater abstracted is used to irrigate 30 percent of the total irrigated area and overall, groundwater provides 20 percent of the total water used for irrigation in Spain (Molinero *et al*, 2011).

Historically, groundwater abstraction rights in Spain were tied to land ownership. The first Spanish ***Water Law*** in 1879 gave private groundwater rights to every land owner: thus groundwater was defined as a private domain and remained outside the control of the state.

The first major reform of the 1879 Water Law only occurred in 1985. The new Water Law re-defined groundwater abstraction rights and declared all aquifers as public domain: the state would regulate groundwater abstractions through concessions for all users issued by ***River Basin Authorities***. The law however left the historical private groundwater rights in the hands of their owners, giving them the possibility to either: a) retain their private property rights until 2038 and then seek to convert them to a concession, or b) to remain private permanently but to register their rights in the Catalogue of Private Waters (Molinero *et al*, 2011).

The reticence of groundwater users to lose any formal historical private rights coupled with the inability, lack of funds and the politically controversial aspect of enforcing these measures by the government has led to a situation where thousands of wells have been constructed outside the ***regulatory framework*** established by the 1985 Water Law (Fornes Ascoiti *et a*l, 2005). Despite different state-wide programs since the mid-1990s to rectify the lack of control of groundwater abstractions and to quantify and establish an inventory of groundwater rights in Spain, the results have been partial and inconsistent due to ***lack of funding*** and difficulties with the cooperation of farmers and well owners (Fornes Ascoiti *et al*., 2005). Additionally, the ***increasing politicization of water management*** competencies between River Basin Authorities, the newly formed regional governments after the end of 40 years of centralizing dictatorship, and the central Government in Madrid, has also helped fuel the conflict between users and the state. As a result, although the official number of wells is officially around half a million, studies have ventured to suggest that up to 2 million wells might exist in Spain (Molinero *et al.,* 2011).

<u>*Groundwater over-abstraction in Spain: the case of La Mancha and Aquifer 23*</u>

Until 1985 the non-regulation and lack of public control associated with the establishment of ***exclusively private groundwater abstraction rights*** went in parallel with the development of intensive irrigation and the increase in crop yields which brought significant economic and social benefits for agrarian communities. The fact that no mechanisms to control groundwater abstractions existed led to an unsustainable situation where socio-economic structures depended on fragile environmental processes of groundwater replenishment.

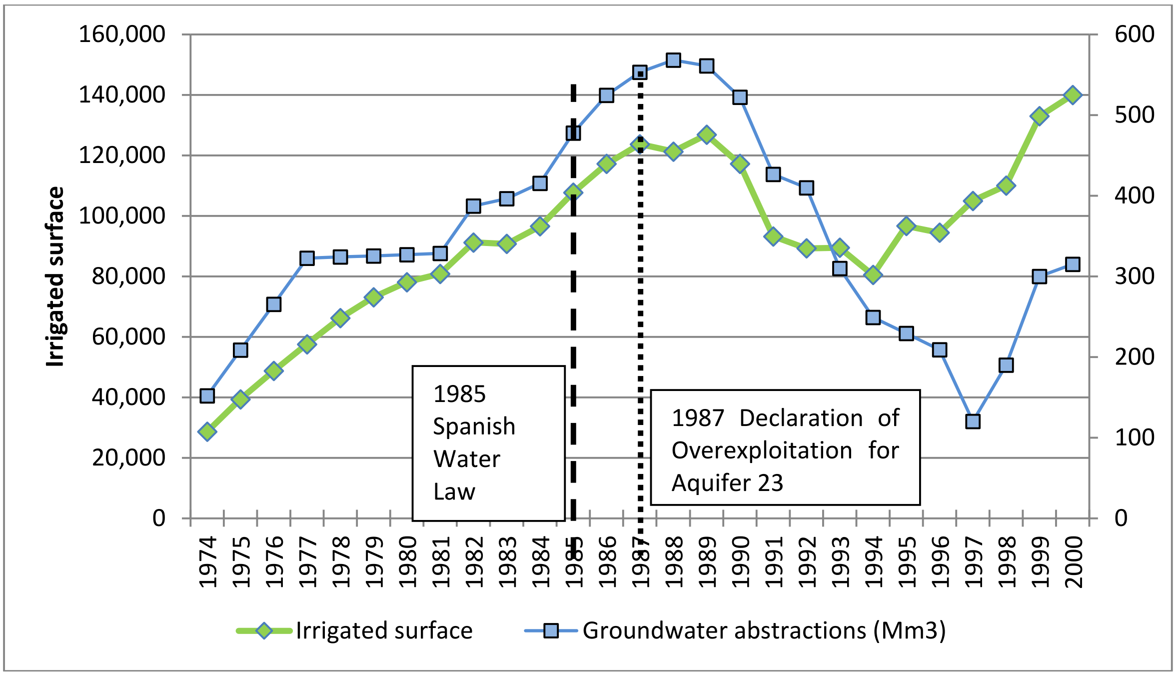
In the region of Castilla-La Mancha (Central Spain), traditional groundwater irrigation helped with a shallow water table served to sustain the basic food needs of the population. Aquifer 23 in La Mancha naturally covered 55,000 hectares holding more than 12,000 million cubic meters of water before modern irrigation began in the 1970s. The transformation of dry and extensive agriculture into intensive groundwater irrigation through large public irrigation projects and the support of private initiative through ***subsidies*** (national and European through the Common Agricultural Policy) caused the water table to fall by up to one meter a year in the past thirty years. From the 1970s to the 1990s, groundwater irrigated land increased from 34,000 hectares to 130,000 hectares (See Figure A8-1). By 1987 the irrigation area represented 6.6 percent of the total increase in irrigated surface at the national level and between 1970 and 1990 the region has seen a ten-fold increase in land area irrigated for agriculture (Bromley *et al.*, 2001).

The ***new legal framework*** put in place with the 1985 Water Law also allowed the State to declare aquifers overexploited and to ***enforce special regulation regimes*** of emergency groundwater abstraction rights. The new Water Law grants River Basin Authorities large management powers to enforce pumping restrictions in both the public and private property regimes as well as the creation of ***groundwater user associations*** (Molinero et al, 2011). For Aquifer 23 in Castilla-La Mancha, the declaration of overexploitation was approved in 1987 along with the emergency management plan for the Aquifer.

In spite of these measures, the ***lack of enforcement and control*** powers by the River Basin Authority, the profitability of water-intensive crops at the time and several drought episodes have led to the increase of illegal pumping since the 1990s. Prosecution by the River Basin Authority of ***illegal abstractions*** and ***unsuccessful***

attempts to install water meters have also partially paralyzed its resources and helped sustain a generalized sense of distrust and impunity amongst farmer groups (Martinez-Santos *et al*, 2008).

Figure A8-1: Irrigated surface and groundwater abstractions in Aquifer 23, La Mancha



Source: Based on Lopez-Gunn & Hernandez Mora (2001) and Martinez Cortina (2011).

Opportunities for groundwater governance in Spain: lessons to be learned

The lack of regulation existing as a consequence of the system of private groundwater rights brought in many places in Spain the depletion of groundwater levels and the development of an ***unsustainable socio-economic and natural disequilibrium***. The depletion of groundwater reserves in places like La Mancha not only emphasizes the need to develop regulatory systems to control groundwater abstractions but also exemplifies the complex and inter-connected reality between natural and social systems.

Under the 1879 Water Law, water user participation was understood in Spain as the right of every irrigator to establish self-governing institutions for the common management of water for irrigation. The changes brought by the new 1985 Water Law expanded this concept and allowed ***collective management*** institutions to have an active presence not only at the local level but also in higher levels of the formal structure of water management decision-making (Lopez-Gunn, 2003).

However, due to the highly politicized water management arena, the acceptance of this new regulatory framework by water users remains incomplete. The negative reaction at the local level of ***top-down imposed initiatives*** and the ***lack of trust*** by many individual farmers and irrigators undermines the proven self-government capacities of this type of institutional arrangements. In addition, unsustainable practices incentivized by heavy public subsidies and animosities between users and the state have also distorted the potential for success of these organizations (Lopez-Gunn & Martinez-Cortina, 2006).

The fragmented political reality of groundwater management institutions in Spain shows the need to establish clear institutional rules to foster the potential of local social capital for groundwater management. However, these rules have to be accompanied by flexible and adaptive solutions aligned with the different social, economic and environmental needs derived from the use of groundwater.

The ***lack of independent and de-politicized groundwater knowledge*** increases the levels of uncertainty and conflict and decreases the capacities of individuals and the state to jointly address the need for sustainable groundwater management. The use of ***modern technology*** to monitor and map groundwater abstraction (e.g. meters, Remote Sensing) needs to be implemented and used in the hands of independent regulation.

Finally, management of groundwater governance in Spain also needs to pay attention to the ***transitional stages of groundwater governance regimes***: the translation of historical abstraction rights (private rights) into new institutional structures (concession, regulation and control) might open the door to future conflicts which can remain latent for a long time. Such management needs to be flexible to cope with the sometimes chaotic nature of groundwater abstraction rights, which can become challenging without strict regulation and enforcement.

Jordan

Jordan is one of the world's most water-scarce countries. In response to historical over-exploitation of many national aquifers, a 1997 ***national water strategy*** (supported by the World Bank) promoted a paradigm shift from supply augmentation towards ***demand-management instruments***[32] to help control groundwater abstraction. It was intended to maximize utilization and minimize wastage through the promotion of water use efficiency and conservation measures to contribute to ***social and economic development and environmental protection***. Pricing policies were deemed to assist in controlling groundwater abstraction and shifting towards higher-value crops. In the 2000s, a ***Groundwater Control Bylaw*** established a quota of 150,000m^3/yr per well and a ***block tariff system*** activated beyond that quote for upland areas. To achieve that, ***Groundwater User Associations*** at the Groundwater Basin level were to be established and ***participatory approaches*** promoted to facilitate cooperation with decision-making authorities. Hence, the national objectives for groundwater are aimed at development of the resource and its protection, management and measures needed to bring the annual abstractions from the various renewable aquifers to the sustainable rate of each.

Hence, the challenge was to devise a system to control illegal groundwater abstraction, license well drilling, and code and record the location of groundwater abstraction sites nationally. To facilitate this, Jordan has established a detailed ***metering system*** and thorough ***national accounting system*** which relates physical water flows to the economy and enables an environmentally extended input-output analysis. Data are collected and analysed from across the country, including real-time and telemetry data, and stored in a central database for analysis. A range of software-based analysis and planning tools have been integrated into national planning and operations processes. The process has been accompanied by a promotion of cooperation between the Ministry of Water Infrastructure (MoWI) and the Department of Statistics (DoS). A ***national water information system*** could ultimately contribute to an even more comprehensive national environmental information system.

The ***groundwater policy*** has comprehensive guidance on many pertinent issues related to resource exploitation; monitoring; resource protection, sustainability, and quality control; resource development; priority of allocation; regulation and control; legislation and institutional arrangements; research, development and technology transfer; shared groundwater resources; and public awareness. Some of the more innovative guidance sub-issues include: specific investigation of brackish waters for augmentation purposes; compilation of oil and gas drilling data to understand deep aquifer potentials; advanced technology utilization i.e. telemetry and automation; specific fossil aquifer management conditions; cooperation with the Ministry of Agriculture to regulate type and application rate of surface applicants; groundwater priority allocation to activities deemed to have higher returns in economic and social terms; comprehensive groundwater basin management plan for each aquifer; cooperation with other organizations which may impact the water sector; regional data exchange; and farmer education on groundwater protection.

Whilst many see Jordan as an example which may have replication potential for other MENA countries and beyond, authors such as Venot & Molle (2008) question the merits of increasing volumetric charges by suggesting that prices may be unlikely to regulate groundwater abstraction and that significant reduction may only be achieved through policies that reduce the number of wells in use. Perhaps only time will tell whether Jordan's approach is effective and sustainable.

Sources: Venot & Molle, 2008; Al-Jayyousi, 2000; MoW&I, nd; Solutions for Water, nd.

[32] Demand management options include measures as diverse as participatory water management, modernization and rehabilitation of existing water supply projects, technical on-farm improvements, conservation methods, reuse of treated wastewater, rainwater harvesting, water pricing or reallocation policies, etc. (Venot & Molle, 2008).

Thematic Paper 12

WATER AND CLIMATE CHANGE:
IMPACTS ON GROUNDWATER RESOURCES AND ADAPTATION OPTIONS

By

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Acknowledgments

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Abbreviations and Acronyms

AAA	Advisory and analytic activities
ACRA	Country Adaptation to Climate Risk Assessment
ADWR	Arizona Department of Water Resources
AFR	Africa Region
AMCOW	African Minister's Council on Water
AOGCM	Atmospheric-Ocean General Circulation Model
AS/NZS	Australian Standards/New Zealand Standards
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Treatment and Recovery
AWS	Assured Water Supply
CAP	Central Arizona Project
CAS	Country Assistance Strategy
CC	Climate Change
CDM	Clean Development Mechanism
CEIF	Clean Energy for Development Investment Framework
CF	Carbon Finance
COP	Conference of the Parties
CO_2	Carbon dioxide
CPIA	Country Policy and Institutional Assessment
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
DEC	Development Economics Department
DPL	Development policy lending
EAP	East Asia and the Pacific
ECA	Europe and Central Asia
ECHAM4	Fourth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (MPI)
ENSO	El Niño-Southern Oscillation
ESMAP	Energy Sector Management Assistance Program
4AR	Fourth Assessment Report (IPCC)
FAR	First Assessment Report (IPCC)
GCM	General Circulation Model
GDE	Groundwater Dependent Ecosystem
GDP	Gross domestic product
GEF	Global Environment Facility
GHG	Greenhouse gases
GL	Giga litre
GMA	Groundwater Management Area
GNI	Gross National Income
GPG	Global public good

GRAPHIC	Groundwater resource assessment under the pressures of humanity and climate changes
GSS	Gnangara Sustainability Strategy
GWSP	Global Water System Project
HadCM3	Hadley Centre Coupled Model, Version 3
IAH	International Association of Hydrogeologists
IBRD	International Bank for Reconstruction and Development
IDA	International Development Association
IFC	International Finance Corporation
IGRAC	International Groundwater Resources Assessment Centre
IHP	International Hydrological Programme
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPO	Inter-decadal Pacific Oscillation
IWSS	Integrated Water Supply System
km	Kilometre
LCR	Latin America and the Caribbean
MAR	Managed Aquifer Recharge
MCA	Multi-Criteria Analysis
MCE	Multiple Criteria Evaluation
MDG	Millennium Development Goals
MIGA	Multilateral Investment Guarantee Agency
ML	Mega litre
MNA	Middle East and North Africa
MOSES	Met Office Surface Exchange Scheme
NAO	North Atlantic Oscillation
NAPA	National Adaptation Programme of Action
NVB	Newer Volcanic Basalt
ODA	Official Development Assistance
PCL	Port Campbell Limestone
PCMDI	Program for Climate Model Diagnostics and Intercomparison
PPIAF	Public-Private Infrastructure Advisory Facility
ppm	parts per million
PPP	Public-Private Partnership
PRSP	Poverty Reduction Strategy Paper
PSDI	Palmer Drought Severity Index
RCM	Regional Climate Model
SADC	South African Development Community
SAR	Second Assessment Report (IPCC)
SAR	South Asia Region
SCCF	Special Climate Change Fund
SD	Statistical Downscaling
SEA	Strategic Environmental Assessment
SKM	Sinclair Knight Merz
SRES	Special Report on Emissions Scenarios

SSA	Sub-Saharan Africa
STP	Sewage treatment plant
SWAp	Sector-wide approach
TA	Technical assistance
TAR	Third Assessment Report (IPCC)
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WA	Western Australia
WBG	World Bank Group
WGHM	WaterGAP Global Hydrology Model
WDR	World Development Report

Executive Summary

Adaptation to climate impacts on groundwater resources in developed and developing countries has not received adequate attention. This reflects the often poorly understood impacts of climate change, the hidden nature of groundwater and the general neglect of groundwater management. Many developing countries are highly reliant on groundwater. Given expectations of reduced supply in many regions and growing demand, pressure on groundwater resources is set to escalate. This is a crucial problem and demands urgent action.

This report addresses the impacts of climate change on groundwater and adaptation options. It is an abbreviated version of a larger report prepared by Sinclair Knight Merz (SKM)[1] for the World Bank as a special paper for the Water Anchor flagship Climate Change and Water. The larger report will also form one of several thematic papers for the new global groundwater governance project that is under preparation by the World Bank.

The importance of groundwater in a changing climate

The Earth's climate is projected to become warmer and more variable. Increased global temperatures are projected to affect the hydrologic cycle, leading to changes in precipitation patterns and increases in the intensity and frequency of extreme events; reduced snow cover and widespread melting of ice; rising sea levels; and changes in soil moisture, runoff and groundwater recharge. Increased evaporation and the risk of flooding and drought could adversely affect security of water supply, particularly surface water. Due to these pressures, as well as global population growth, demand for groundwater is likely to increase.

Compared to surface water, groundwater is likely to be much more compatible with a variable and changing climate. Relative to surface water, aquifers have the capacity to store large volumes of water and are naturally buffered against seasonal changes in temperature and rainfall. They provide a significant opportunity to store excess water during high rainfall periods, to reduce evaporative losses and to protect water quality. However these opportunities have received little attention, in part because groundwater is often poorly understood and managed.

Reducing vulnerability through adaptation

Groundwater plays a critical role in adapting to hydrologic variability and climate change. Groundwater options for enhancing the reliability of water supply for domestic, industrial, livestock watering and irrigation include (but are not exclusive to):

- *Integrating the management of surface water and groundwater resources* – including conjunctive use of both groundwater and surface water to meet water demand. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle.
- *Managing aquifer recharge (MAR)* – including building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. MAR is among the most promising adaptation opportunities for developing countries. It has several potential benefits, including storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.
- *Land use change* – changing land use may provide an opportunity to enhance recharge, to protect groundwater quality and to reduce groundwater losses from evapotranspiration. Changes in land use should not result in adverse impacts to other parts of the environment.

[1] Sinclair Knight Merz (SKM). 2009. Adaptation options for climate change impacts on groundwater resources. Victoria. Australia. The larger report: (a) characterizes the impact of current and projected hydrologic variability and Climate Change on groundwater, (b) develops a Methodology for Assessing Vulnerability and Risk in Groundwater Dependent Water Systems to Hydrological Variability and Climate Change and (c) presents four developed nation case studies from Australia, Europe, or the United States. The methodology for assessing vulnerability and risk developed under the larger report was omitted in the abbreviated report in order to avoid confusion with the methodology presented in the flagship report.

Groundwater is also vulnerable to climate change and hydrological variability. Potential climate risks for groundwater include reduced groundwater recharge, sea water intrusion to coastal aquifers, contraction of freshwater lenses on small islands, and increased demand. Groundwater can also be affected by non-climatic drivers, such as population growth, food demand and land use change. Active consideration of both climatic and non-climatic risks in groundwater management is vital.

Effective decision making

Effective, long term adaptation to climate change and hydrologic variability requires measures which protect or enhance groundwater recharge <u>and</u> manage water demand. Adaptation to climate change can't be separated from actions to improve management and governance of water reserves (e.g. education and training, information resources, research and development, governance and institutions).

Adaptation needs to be informed by an understanding of the local context, and of the dominant drivers (and their projected impact) on groundwater resources in the future. Adaptations must be carefully assessed to ensure investment in responses to climate change and hydrological variability is proportional to risk and that they do not inappropriately conflict with other social, economic, resource management or environmental objectives. Adaptations should not add further pressures on the global climate system by significantly increasing greenhouse gas emissions.

Adaptation options need to be economically viable. In some cases the cost and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met. An economic assessment of adaptation options should factor any initial and ongoing costs, and means for financing these. It must also take into account the local economic environment, which can vary significantly between and within nations.

Adaptation can start now

In many cases, adaptations to reduce the vulnerability of groundwater dependent systems climatic pressures are the same as those required to address non-climatic pressures, such as over-allocation or overuse of groundwater. Such 'no regrets' adaptations can be implemented immediately in areas where water resources are already stressed, regardless of concerns about the uncertainty of climate change projections and assessments of impact on groundwater and surface water resources.

Successful examples of groundwater adaptation to climate change and hydrologic variability exist in both developed and developing nations. A list of available adaptation options is included in this report. Adaptation case studies from three developed nations (England, America and Australia) are also provided.

Recommendations

To improve the Bank and client country capacity for and uptake of groundwater adaptation, the following next steps are recommended:

1. **Support adaptation case studies in developing nations** – adaptation case studies from three developed nations were reviewed in the current report. As part of the global groundwater governance project, a series of in-depth case studies and evaluations are recommended to be prepared for developing countries. Possible case study countries could include: Brazil, China, India, Kenya, Mexico, Morocco, Philippines, South Africa, Tanzania and Yemen. The following transboundary aquifers might also be considered to be part of these case studies:
    - the Nubian sandstone aquifer system – this aquifer is located in north-eastern Africa and spans the political boundaries of four countries: Chad, Egypt, Libya and Sudan;
    - aquifers that span across the fourteen countries in the South African Development Community (SADC).

These case studies would provide policy and operational guidance (lessons and experiences) to water resource managers in similar settings on improving groundwater governance and conceptualizing and implementing adaptation programs. As a minimum the case studies should focus on examples of MAR, improved management of groundwater storage, conjunctive use, planning and management of groundwater and surface water and reform of water governance. The case studies should cover a range of biophysical and institutional settings and be representative of different kinds of experienced climate change or climate risk impact.

2. **Promote groundwater management and development opportunities** – identify and integrate opportunities to manage and develop groundwater in future water sector programs to improve the reliability of water supply for multiple uses and protection of ecosystems. This may include supporting:
   - Assessment of the suitability of MAR – to determine the potential viability for MAR. This assessment should identify areas of current water stress (i.e. need), water availability (e.g. excess wet season surface flows, treated waste water), potential storage, and the likelihood that groundwater quality will be suitable for the required use/s. Any planning for MAR should be coupled with demand management strategies.
   - Capacity building in groundwater management and planning. This may include activities such as groundwater resource assessments to better understand the resource, establishing and populating groundwater databases, increasing the level of hydrogeological expertise by establishing or improving accessibility to groundwater training institutions, a manual for groundwater management to outline minimum good practice standards etc.
   - More integrated management of water resources. This may include conjunctive water use and assessing the impacts of existing or proposed infrastructure to identify any potential inefficiencies or adverse impacts that may be treated to achieve optimal use of water resources.

3. **Disseminate knowledge** - Information from this report and developing country case studies should be disseminated to World Bank staff as part of the overall sector analysis on Climate Change and Water.

4. **Collaborate with programs and partner agencies with specialized knowledge –** including:
   - Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) – the GRAPHIC project is hosted by IHP-UNESCO, IGRAC and GWSP and focuses on understanding the impacts of climate change and other pressures for groundwater, globally;
   - International Association of Hydrogeologists (IAH), and
   - International Groundwater Resource Assessment Centre (IGRAC)

1. Introduction

There is understandable concern about the potential impacts of human-induced climate change on water resources. While at a global level rainfall should increase due to increased evaporation, this change will be unevenly distributed and many regions are projected to receive substantially less rain (IPCC, 2007). When combined with increased temperatures, the retreat of glaciers, rising sea levels and increasing demand for fresh water from rapidly growing populations, the pressure on water resources is set to escalate.

Concern about climate change and water resources has translated into an impressive array of studies of potential impacts and adaptations. However, in comparison to surface water resources, the level of attention paid to groundwater, particularly in developing countries, has been limited. This reflects the hidden nature of groundwater, the general neglect of its management, as well as uncertainties about the potential impacts of climate change.

This report – Water and Climate Change: Impacts on groundwater resources and adaptation options - has been prepared as a special paper for the World Bank flagship on Climate Change and Water. The flagship covers Climate Change and Water issues from a broad and multi-sectoral perspective. This report is an abbreviated version of a larger report prepared by SKM for the World Bank[2]. The larger report will also form one of the thematic papers for the global groundwater governance project that is under preparation by FAO and the World Bank.

1.1 Groundwater in World Bank regions

Groundwater and soil moisture collectively account for over 98% of global fresh water resources, with more than two billion people dependent on groundwater for their daily supply (Hiscock, 2005). Groundwater is a major source of water for agriculture and to meet basic human needs in developing countries.

While not the dominant source of water in any of the six World Bank regions, groundwater is the major source in several countries (Table 1.1). Groundwater is most intensively developed in the World Bank's Middle East – North Africa and Latin America-Caribbean regions.

The hidden nature of groundwater, its resilience in the face of short-term climatic variability and the difficulty in measuring it, have, among other factors, contributed to its poor management and the growing stress on groundwater resources. In many countries, even developed countries with robust surface water management arrangements, groundwater use is unregulated and poorly planned and managed. Unsustainable management has resulted in the depletion of groundwater in both developed and developing nations (Figure 1.1). Usage often exceeds average annual recharge. In some North African and Middle East nations, water use exceeds recharge by a factor of three (IGRAC, 2004; http://igrac.nitg.tno.nl/ggis_map/start.html).

Pressures on surface water resources are intensifying, due to growth in population, increased demand for food, pollution and (in some regions) climate change. As this occurs, these pressures are increasingly being referred to groundwater and the need for improved management grows.
Groundwater also plays an important role in sustaining a wide range of terrestrial, aquatic and marine ecosystems. For some ecosystems, there is a highly specialized dependency on groundwater; for example for habitat, water supply or survival during drought (e.g. Hatton and Evans, 1998; Clifton and Evans, 2001).

[2] The larger report: (a) characterizes the impact of current and projected hydrologic variability and Climate Change on groundwater, (b) develops a Methodology for Assessing Vulnerability and Risk in Groundwater Dependent Water Systems to Hydrological Variability and Climate Change and (c) presents four developed nation case studies from Australia, Europe, or the United States. The methodology for assessing vulnerability and risk developed under the larger report was omitted in the abbreviated report in order to avoid confusion with the methodology presented in the flagship report.

Table 1.1 Groundwater use in World Bank regions

World Bank region	Groundwater use as % of total water use		Examples of countries where >50% of water is sourced from groundwater
	Average % use across region[1]	Maximum recorded percentage of use	
East Asia and Pacific	19	79	Mongolia
Europe and Central Asia	22	83	Georgia, Lithuania.
Latin America and the Caribbean	32	96	Barbados, Bolivia, Jamaica.
Middle East and North Africa	41	78	Iran, Libya, Tunisia.
South Asia	26	35	-
Africa	18	54	Botswana, Mauritania, Namibia.

[1] Where data available. Source data: IGRAC

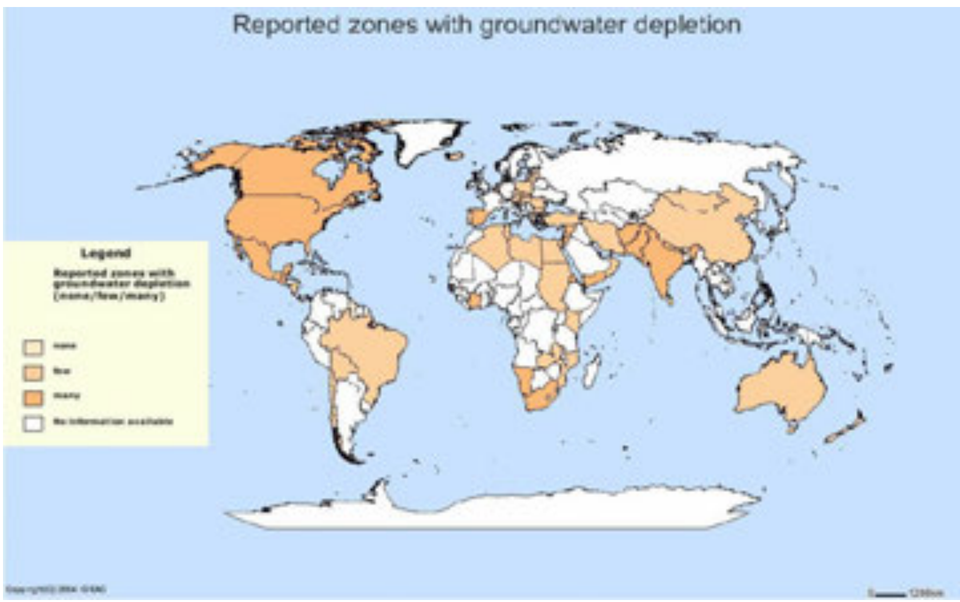

Figure 1.1 Reported countries with groundwater depletion. Source: IGRAC Global Groundwater Information System.
Source: http://igrac.nitg.tno.nl/ggis_map/start.html

1.2 Climate change

Atmospheric concentrations of carbon dioxide and other greenhouse gases are increasing. There is a growing body of evidence that this is already contributing to changes in climatic conditions, with impacts on hydrological cycles evident at some locations (IPCC, 2007). Global change scenarios anticipate further large increases in greenhouse gas emissions over the course of this century, with consequences for climate including increased surface temperature, changes in the amount and pattern of precipitation and increased potential evaporation. The nature of these changes is projected to vary across the globe. The critical threats to groundwater (and dependent systems) from these changes is reduced availability of groundwater, due to reduced groundwater recharge, increased demand or groundwater contamination (Section 2.2). The implications for socio-economic and environmental conditions in vulnerable regions could be very serious. There is a 'basic need to identify the sensitivity of groundwater to climate variability and change' (GRAPHIC, 2008). Adaptation is required to address the risks faced and improve the resilience of groundwater dependent communities and environments.

1.3 About this report

This report is a special paper for the Water Anchor flagship Climate Change and Water. Its overall objective is to develop an analytical framework for improving the resilience of groundwater dependent communities and environments in the face of threats from increasing demand, unsustainable management and reduced availability due to climate change. A broader goal of the paper is also to promote and elevate the role of groundwater in integrated water resources management (IWRM).

The analysis of the impacts of climate change on groundwater and adaptation was planned to be carried out in two phases. The first phase is reported here. It includes a literature review of the current and projected impact of hydrologic variability and climate change on groundwater and of adaptation options for groundwater resources. A methodology for assessing vulnerability and risk to hydrologic variability and climate change in groundwater dependent water systems has also been developed and is part of the larger report. Several case studies have been prepared, which outline adaptations to improve the resilience of groundwater systems to climate change and hydrological variability in Australia, the United States of America and the United Kingdom.

This report also proposes the scope of subsequent phases which will be supported under the new global groundwater governance project and will (a) identify, assess and begin to implement adaptation options for improving the resilience of groundwater systems in selected developing nations and (b) disseminate project outputs to World Bank staff working in water supply, irrigation and water resources management.

The target audience is technical and non-technical water supply, irrigation, water resources and environmental specialists from the Bank, other institutions and client nations.

This report is structured as follows:
Section 1: Introduction – briefly summarizes the context, purpose and scope of the project
Section 2: Climate change, hydrological variability and groundwater – a review of the linkages between groundwater and climate, the impacts of climate change on groundwater resources, and implications for groundwater dependent systems. A discussion of the existing knowledge status and identified data and knowledge gaps is also included.
Section 3: Adaptation options – a review and assessment of adaptation options to improve the resilience of groundwater systems to risks posed by hydrological variability and climate change.
Section 4: Case studies – a summary of three case examples where groundwater adaptation options have been employed.
Section 5: Conclusion
Section 6: Recommendations

2. Climate change, hydrological variability and groundwater

2.1 Fundamental concepts

2.1.1 Groundwater and the hydrologic cycle

The *hydrologic cycle* (Figure 2.1) represents the continuous movement of water between the atmosphere, the Earth's surface (glaciers, snowpack, streams, wetlands and oceans) and soils and rock. The term *groundwater* refers to water in soils and geologic formations that are fully saturated.

The hydrologic cycle is driven by solar energy which heats the Earth's surface and causes water from the Earth's surface to evaporate, sublimate and transpire. Water is transported from the atmosphere back to the Earth's surface as precipitation, falling as either rain or snow.

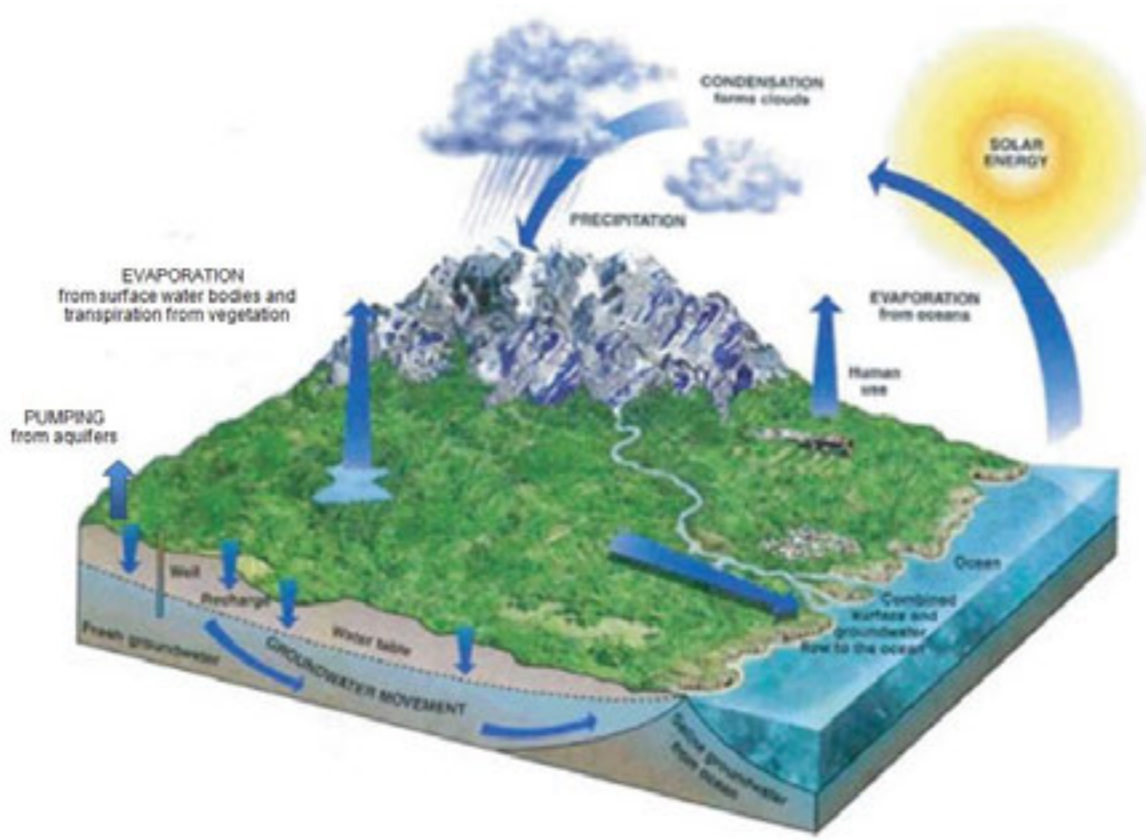

Figure 2.1 The hydrologic cycle.

Source: http://www.pvwma.dst.ca.us/hydrology/images/hydrologic_cycle.jpg

Exchange of atmospheric water to groundwater can occur via infiltration of rainfall or snowmelt through the soil profile. Water may also run off the Earth's surface and infiltrate to groundwater via stream channels and wetlands. The process by which water from the surface enters the groundwater system is called *recharge*.

Loss of groundwater to the atmosphere occurs through the process of evapotranspiration. This includes direct evaporation of shallow groundwater and transpiration by vegetation. Groundwater may also flow into streams, springs, wetlands and oceans, or be pumped from wells for human use. The process by which water is lost from groundwater is called *discharge*. The difference between recharge and discharge determines the volume of water in groundwater storage.

Any variations in climate have the potential to affect recharge, discharge and groundwater quality, either directly or indirectly. An example of a direct impact would be reduced recharge due to a decrease in precipitation. Sea water intrusion to coastal aquifers due to increased temperature and subsequent sea level rise represents an indirect influence on groundwater quality.

Groundwater quantity and quality can also be affected by water and land use change. Examples include changes to groundwater pumping regimes, damming of rivers, clearing of woody vegetation and conversion of dryland agriculture to irrigation.

2.1.2 Climate change and hydrologic variability

Climate change is "an altered state of the climate that can be identified by change in the mean and/or variability of its properties and that persist for an extended period, typically decades or longer" (Bates et al., 2008). It may be due to "natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC, 2007).

Over the past 150 years global mean temperatures have increased with the rate of warming accelerated in the past 25 to 50 years. It is considered very likely that this change is largely attributed to anthropogenic influences (in particular increased CO_2 concentrations from burning of fossil fuels) and that global warming will continue in the future (IPCC, 2007).

Climate also varies in response to natural phenomena, on seasonal, inter-annual, and inter-decadal scales. Examples of these natural phenomena include the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the North Atlantic Oscillation (NAO) and the Interdecadal Pacific Oscillation (IPO). The presence of, and degree of influence from, these and other natural phenomena will vary between countries and even watersheds.

Variations in climate will induce hydrologic change. Table 2.1 summarizes the variations in climate and hydrology that are projected to occur due to global warming. The potential impacts of these changes for groundwater resources are discussed in subsequent sections.

2.2 Impacts of climate change on groundwater

2.2.1 Recharge

Groundwater recharge[3] can occur locally from surface water bodies or in diffuse form from precipitation via the unsaturated soil zone (Döll and Fiedler, 2008). Precipitation is the primary climatic driver for groundwater recharge. Temperature and CO_2 concentrations are also important since they affect evapotranspiration and thus the portion of precipitation that may drain through the soil profile to aquifers. Other factors affecting groundwater recharge include land cover, soils, geology, topographic relief and aquifer type.

The only global scale estimates of climate change impacts to groundwater recharge are those developed by Döll and Flörke (2005). Based on calculations from the global hydrological model WGHM (WaterGAP Global Hydrology Model), they estimated diffuse recharge (1961-1990 baseline) at the global scale with a resolution of 0.5° by 0.5°. They then simulated the impacts of climate change for 2050s under a high (A2) and low (B2) greenhouse gas emission scenario. Other scenarios (e.g. 2030 time frame, A1B greenhouse gas emissions) were not modelled in this work and therefore cannot be reported here.

[3] The focus of this section is on natural recharge, not artificial recharge. Artificial recharge occurs due to excess irrigation or via intentional enhancement of recharge. The latter is commonly known as managed aquifer recharge (MAR). MAR is discussed further in Section 2.4.1.

Table.2.1 Projected impact of global warming for primary climate and hydrologic indicators

Variable	Projected future change*
Temperature	Temperatures are projected to increase in the 21st century, with geographical patterns similar to those observed over the last few decades. Warming is expected to be greatest over land and at the highest northern latitudes, and least over the Southern Oceans and parts of the North Atlantic ocean. It is very likely that hot extremes and heat waves will continue to become more frequent.
Precipitation	On a global scale precipitation is projected to increase, however this is expected to vary geographically - some areas are likely to experience an increase and others a decline in annual average precipitation. Increases in the amount of precipitation are likely at high latitudes. At low latitudes, both regional increases and decreases in precipitation over land areas are likely. Many (not all) areas of currently high precipitation are expected to experience precipitation increases, whereas many areas of low precipitation and high evaporation are projected to have precipitation decreases. Drought-affected areas will probably increase and extreme precipitation events are likely to increase in frequency and intensity. The ratio between rain and snow is likely to change due to increased temperatures.
Sea level rise	Global mean sea level is expected to rise due to warming of the oceans and melting of glaciers. The more optimistic projections of global average sea level rise at the end of the 21st century are between 0.18-0.38 m, but an extreme scenario gives a rise up to 0.59 m. In coastal regions, sea levels are likely to also be affected by larger extreme wave events and storm surges.
Evapo-transpiration	Evaporative demand, or potential evaporation, is influenced by atmospheric humidity, net radiation, wind speed and temperature. It is projected generally to increase, as a result of higher temperatures. Transpiration may increase or decrease.
Runoff	Runoff is likely to increase at higher latitudes and in some wet tropics, including populous areas in East and South-East Asia, and decrease over much of the mid-latitudes and dry tropics, which are presently water stressed. Water volumes stored in glaciers and snow cover is likely to decline, resulting in decreases in summer and autumn flows in affected areas. Changes in seasonality of runoff may also be observed due to rapid melting of glaciers and less precipitation falling as snow in alpine areas.
Soil moisture	Annual mean soil moisture content is projected to decrease in many parts of the sub-tropics and generally across the Mediterranean region, and at high latitudes where snow cover diminishes. Soil moisture is likely to increase in East Africa, central Asia, the cone of South America, and other regions with substantial increases in precipitation.

*Relative to 1990 baseline. Source: IPCC (2007), World Bank (2009)

According to the results of Döll and Flörke (2005), recharge – when averaged globally for the 2050s – will increase by 2%. This is less than the projected increases of 4% and 9% for annual precipitation and runoff. Geographical variations in Döll and Flörke's (2005) 2050 recharge projections (Figure 2.2) include:

- significant decreases in groundwater recharge (by more than 70%) for north-eastern Brazil, the western part of southern Africa and areas along the southern rim of the Mediterranean Sea
- increased groundwater recharge (by greater than 30%) across large areas, including the Sahel, Northern China, Western US and Siberia
- potentially significant decreases in groundwater recharge for Australia, USA and Spain, although results vary significantly between climate models in these areas.[4]

[4] This is relative to 1961-1990 recharge rates which in many cases may be very low. Uncertainties associated with projected change in precipitation from global climate model models also apply here.

These global estimates identify regions where groundwater is potentially vulnerable to climate change. However, they are not appropriate for scaling down to a country or watershed scale. Precipitation and groundwater systems can vary significantly between watersheds and this variability has not been incorporated into Döll and Flörke's (2005) modelling. Also, their method only represents diffuse recharge – recharge from rivers or other surface waters were not accounted for.

Changes in the magnitude of groundwater recharge will not always be in the same direction as precipitation changes. Recharge is not only influenced by the magnitude of precipitation, but also by its intensity, seasonality, frequency, and type (figure 2.3). Other factors, for example changes in soil properties or vegetation type and water use can also affect recharge rates. Van Roosmalen et al. (2007) concluded that changes to groundwater recharge rates were highly dependent on the geological setting of the area.

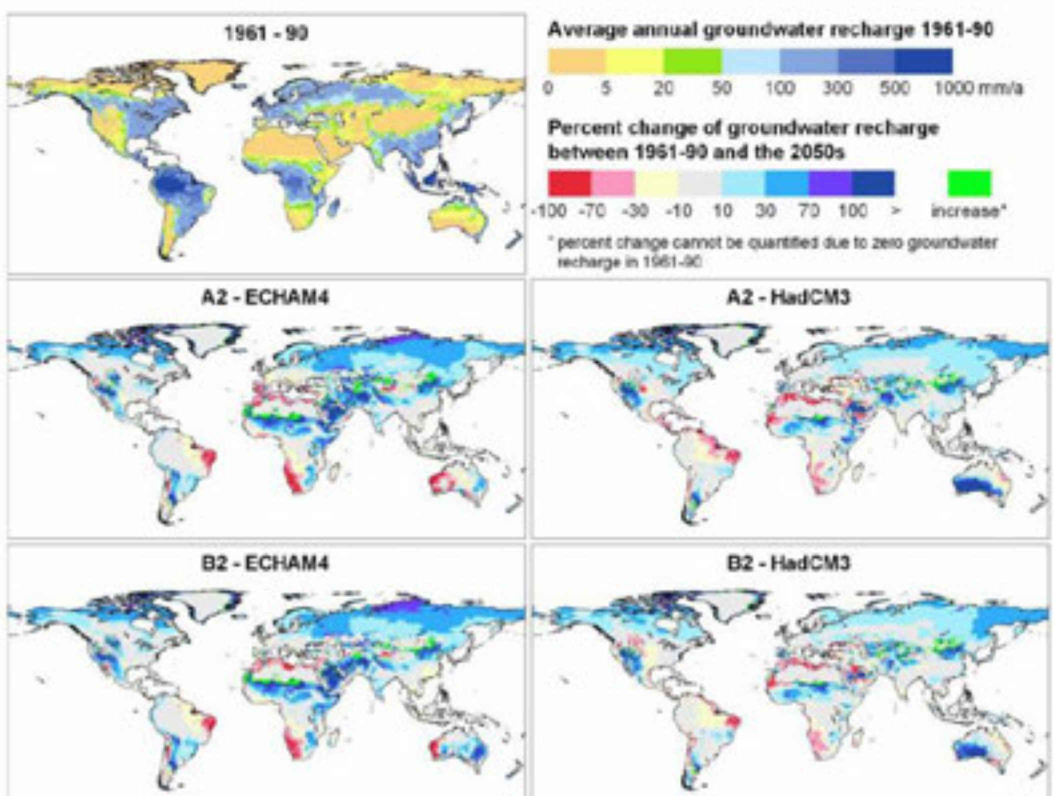

Figure 2.2 Global estimates of climate change impact on groundwater recharge.

Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961-1990 and the 2050s (2041-2070), as computed by WGHM applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions scenarios A2 and B2). Source: Döll and Flörke (2005).

During high intensity rainfall events the infiltration capacity of soils may quickly be exceeded, resulting in increased runoff and stream flow with less rain infiltrating to groundwater (Acreman, 2000). More frequent and longer droughts may lead to soil crusting and hydrophobic soils, such that during precipitation events overland flow increases and groundwater recharge decreases (Döll and Flörke, 2005). In areas where groundwater is recharged from surface water bodies or via preferential pathways such as macropores and joints, higher intensity rainfall is likely to lead to more groundwater recharge (Döll and Flörke, 2005; van Vliet, 2007).

High latitude regions

Recharge may occur earlier due to warmer winter temperatures, shifting the spring melt from spring toward winter.

In areas where permafrost thaws due to increased temperatures, increased recharge is likely to occur.

Temperate regions

Changes to annual recharge will vary depending on climate and other local conditions.

In some cases little change may be observed in annual recharge, however the difference between summer and winter recharge may increase.

Arid and semi-arid regions

In many already water stressed arid and semi arid areas, groundwater recharge is likely to decrease.

However where heavy rainfalls and floods are major sources of recharge, an increase in recharge may be expected. E.g., alluvial aquifers where recharge occurs via stream channels, or bedrock aquifers where recharge occurs via direct infiltration of rainfall through fractures or dissolution channels.

Figure 2.3 Summary of climate change impacts on recharge under different climatic conditions.

Source: Holman et al, 2001; Döll and Flörke, 2005; van Vliet, 2007; Dragoni and Sukhija, 2008.

Precipitation changes during the major recharge season are likely to be more significant than annual changes. Yet this will also be influenced by antecedent conditions on a seasonal and inter-annual scale. More frequent droughts or reduced rainfall during summer months can result in larger soil moisture deficits, and consequently recharge periods may be shortened (Acreman, 2000; Holman, 2006; Döll and Florke, 2005). This may be exacerbated by increased temperatures and evapotranspiration, although the effects of climate change on transpiration from vegetation is uncertain (Section 2.2.2).

In high latitude regions, recharge may occur earlier as warmer winter temperatures shift the spring melt from spring toward winter (van Vliet, 2007). Where permafrost thaws due to increased temperatures, increased recharge is likely to occur (Dragoni and Sukhija, 2008).

The ratio of change in groundwater recharge to change in rainfall is not 1:1. Green *et al.* (1997) simulated the effects of climate change on groundwater recharge in the Gnangara Mound, Western Australia, by modelling the impacts of increased atmospheric concentrations of CO_2 on rainfall and potential evapotranspiration regimes. They found that the magnitude and even the direction of change in recharge depends on the local soil, vegetation and climatic region and that ratios of the change in recharge to change in rainfall ranged from -0.8 to 0.6 (Figure 2.4)

For the Hawkesdale region in south-eastern Australia, SKM (2007) modelled the impacts of climate change on groundwater recharge under different land cover, depth to water table, geological and climatic conditions. The latter included capturing natural inter-decadal variations in climate, in addition to anthropogenic climate change (further details are provided in the larger report). Across their modelled scenarios, ratios of the change in recharge to change in rainfall ranged from 0 to 0.87. Where rainfall fell below the threshold required to negate runoff and evapotranspirative losses, zero recharge was observed to occur.

Sandstorm (1995) studied a semi-arid basin in Africa and concluded that a 15% reduction in rainfall could lead to a 45% reduction in groundwater recharge. In the Murray Darling Basin (Australia) Crosbie *et al.* (2009) also concluded that the percentage change in groundwater recharge was greater than the percentage change in rainfall, by a factor of approximately 2.2 (Figure 2.5) Furthermore Crosbie *et al.* (2009) found that even when there is no change in rainfall, the increase in temperature caused an increase in the vapour pressure deficit, which resulted in an increase in evapotranspiration and hence a decrease in recharge. The decrease in recharge manifested itself as reduced discharge to streams and hence reduced streamflow. This has very significant implications.

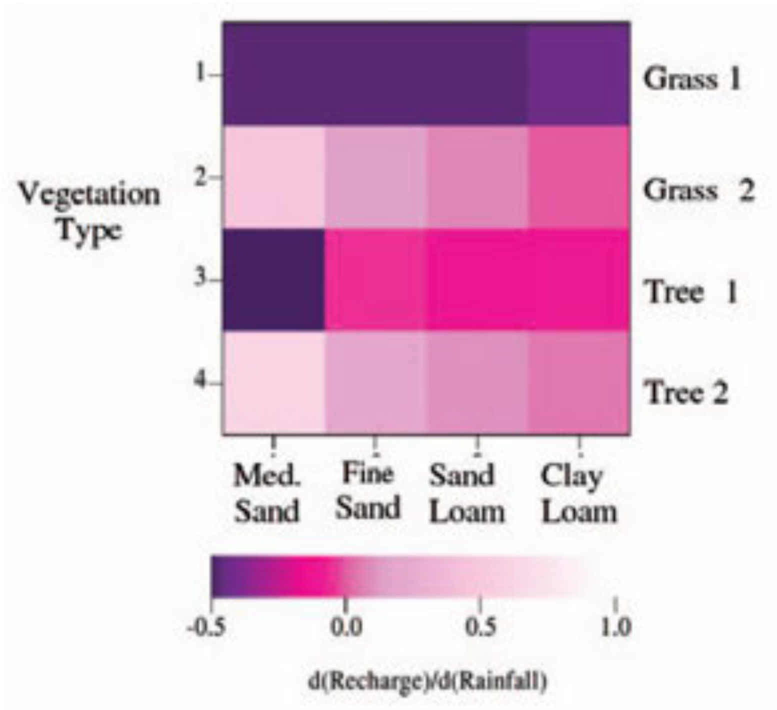

*Figure 2.4 Simulated change in recharge per unit change in rainfall under a double-CO_2 climate change scenario in Western Australia (**Green et al., 1997**).*

Grasses 1 and 2 represent perennial grasses, Trees 1 and 2 represent pine and eucalypt canopies. Reproduced from GRAPHIC (2008).

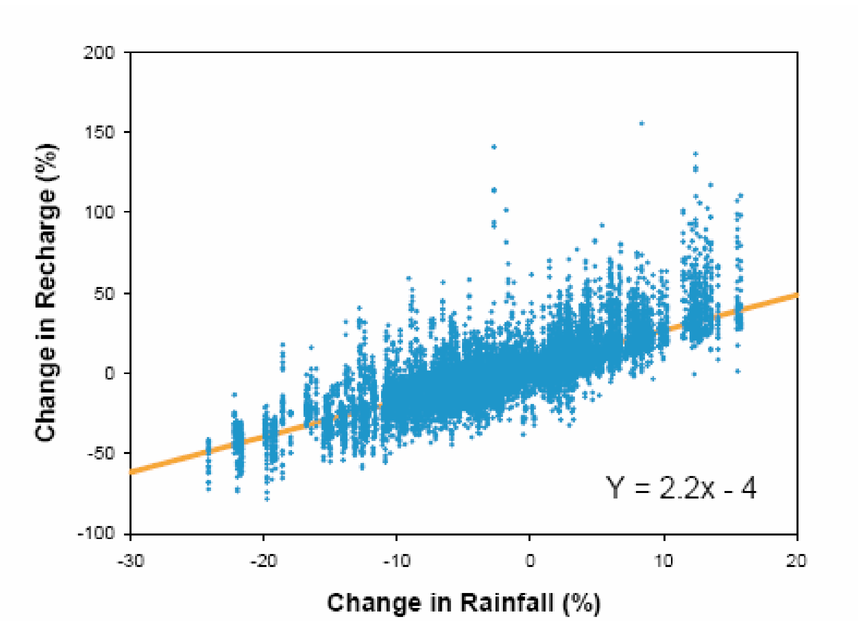

Figure 2.5 Change in rainfall versus change in recharge for Murray Darling Basin, Australia.

Source: Crosbie et al., 2009.

2.2.2 Discharge

The impacts of climate change on groundwater discharge are less well understood. In part this reflects the difficulties in measuring discharge, and thus a lack of data to quantify discharge processes (van Vliet, 2007). Historically groundwater assessments have also been focused on understanding how much water enters the groundwater system and if this is suitable for human use. Less consideration has been given to the ecosystems groundwater supports, such as terrestrial vegetation and groundwater flow to springs, streams, wetlands and oceans.

For evapotranspiration, direct climate change impacts include: (1) changes in groundwater use by vegetation due to increased temperature and CO_2 concentrations, and (2) changes in the availability of water to be evaporated or transpired, primarily due to changes in the precipitation regime.

Whilst CO_2 is likely to be a significant factor in the water balance, the extent of its impact is still uncertain (Kruijt *et al.*, 2008). Experimental evidence shows that elevated atmospheric CO_2 concentrations tend to reduce stomatal opening in plants, and that this leads to lower transpiration rates (Bethenod *et al.*, 2001; Kruijt *et al*., 2008). In a study for the Netherlands, Kruijt *et al*. (2008) concluded that the combined effects of CO_2 on evapotranspiration ranged between a few percent for short crops to about 15% for tall rough vegetation, and that this was of a 'comparable but opposite magnitude to predicted temperature-induced *increases* in evapotranspiration'.

Increased duration and frequency of droughts (due to increased temperatures and increased variation in precipitation) is likely to result in greater soil moisture deficits. Where soil water becomes depleted, vegetation may increasingly depend on groundwater for survival (if groundwater occurs in proximity to the root zone). During dry periods this may lead to increased evapotranspiration from groundwater. Indirect impacts associated with land use change may also affect groundwater evapotranspiration. For example, reforestation for CO_2 capture may draw on shallow groundwater and lower water tables (Dragoni and Sukhija, 2008).

Groundwater flow to surface water bodies will be driven by relative head levels between groundwater and surface water. Consequently the effects of climate change are indirect; through alterations to recharge and other discharge mechanisms (e.g. evapotranspiration). If groundwater falls below surface water levels, groundwater discharge may no longer occur (and vice versa). In semi-arid and arid regions, the dependence on groundwater to maintain baseflow in permanent streams is likely to be greater during periods of extended drought. In temperate areas where higher winter recharge is projected (e.g. UK) it is conceivable that some watersheds could sustain higher baseflows during summer, even if summers become warmer and drier (Acreman, 2000).

Groundwater pumping also forms a mechanism for groundwater discharge. Projected increases in precipitation variability are likely to result in more intense droughts and floods, affecting the reliability of surface water supplies with respect to both quantity and quality. Human demand for groundwater is therefore likely to increase to offset this declining surface water availability and, where available, will become a critical facet for communities to adapt to climate change (Foster, 2008).

Large volumes of groundwater, often of acceptable quality, discharge to oceans in near shore environments. This discharge process, and the capacity for recovery of groundwater, is currently poorly understood (Dragoni & Sukhija, 2008).

2.2.3 Groundwater storage

Groundwater storage is the difference between recharge and discharge over the time frames that these processes occur, ranging between days to thousands of years. Storage is influenced by specific aquifer properties, size and type. Deeper aquifers react, with delay, to large-scale climate change but not to short-term climate variability. Shallow groundwater systems (especially unconsolidated sediment or fractured bedrock aquifers) are more responsive to smaller scale climate variability (Kundzewicz and Döll, 2008). The impacts of climate change on storage will also depend on whether or not groundwater is renewable (contemporary recharge) or comprises a fossil resource.

2.2.4 *Water quality*

In many areas, aquifers provide an important source of freshwater supply. Maintaining water quality in these aquifers is essential for the communities and farming activities dependent on them. Both thermal and chemical properties of groundwater may be affected by climate change. In shallow aquifers, groundwater temperatures may increase due to increasing air temperatures. In arid and semi-arid areas increased evapotranspiration may lead to groundwater salinization (van Vliet, 2007). In coastal aquifers, sea level rise and storm surges are likely to lead to sea water intrusion and salinization of groundwater resources. Changes in recharge and discharge (see above) are likely to change the vulnerability of aquifers to diffuse pollution (van Vliet, 2007).

Ranjan *et al.* (2006) assessed the impact of sea level rise on the loss of fresh groundwater resources in coastal aquifers. Their study included coastal areas in the following five regions: Central America, Southern Africa, Northern Africa/Sahara, around the Mediterranean, and in the Southern Asia. Climate change impacts were simulated for a high (A2) and low (B2) emissions scenarios and accounted for changes in groundwater recharge, as per the conceptual model provided in Figure 2.6. With the exception of the Northern Africa/Sahara region, Ranjan et al. (2006) found that a long-term trend of increasing loss of fresh coastal groundwater resources was likely in all studied regions under both high and low emissions scenarios. Small islands and coral atolls, where sea level rise leads to contraction of fresh groundwater lenses, are particularly vulnerable (Kundzewicz & Döll, 2008).

In areas where rainfall intensity is expected to increase, pollutants (pesticides, organic matter, heavy metals etc) will be increasingly washed from soils to water bodies (IPCC, 2007). Where recharge to aquifers occurs via these surface water bodies, groundwater quality is likely to decline. Where recharge is projected to decrease, water quality may also decrease due to lower dilution (IPCC, 2007) and in some cases may also lead to intrusion of poorer quality water from neighbouring aquifers (van Vliet, 2007).

Taylor et al. (2008) assessed the impact of increased heavy rains on the water quality of spring discharge in Kampala, Uganda. They concluded that increased heavy rainfall events would lead to more frequent, episodic deterioration in bacteriological quality of spring discharges, derived from rapid flushing of inadequately contained faecal matter in the area. In areas where groundwater levels rise, waste stored underground in the unsaturated zone may become saturated and contaminate the groundwater resource.

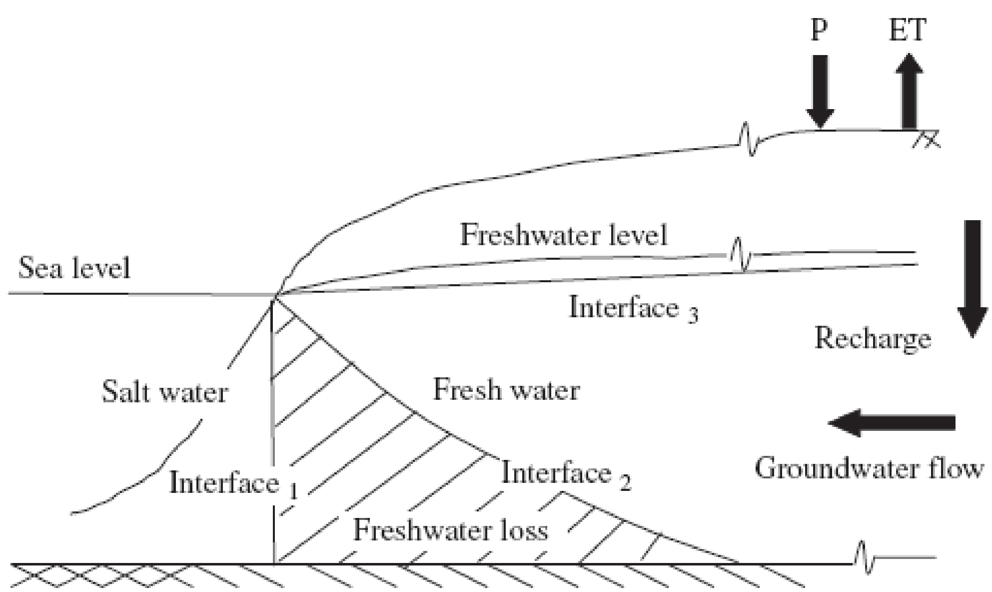

Figure 2.6 Schematic representing the loss of fresh groundwater resources due to saltwater intrusion in coastal aquifers.

Increases in recharge shifts the saltwater interface seaward. Decreases in recharge and/or increases in sea level will result in landward movement of the salt water interface. Source: Ranjan et al. (2006).

2.3 Impacts of non-climatic factors

Whilst climate change is likely to have adverse impacts on the quantity and quality of groundwater resources, in many areas this will be dwarfed by the non-climatic impacts including growth in the global population, food demand (which drives irrigated agriculture), land use change, and socio-economic factors that influence the capacity to appropriately manage the groundwater resource.

Historically, in both developed and developing nations, groundwater demand has been poorly managed. Low investment in groundwater investigations and management during the 20th century, a time of intensive groundwater use for agricultural crop production, has placed groundwater under stress (Hiscock and Tanaka, 2006). Increased groundwater use associated with population growth has also been a factor, particularly in arid and semi-arid areas where water is scarce. Future global population growth is expected to place groundwater resources under greater stress.

Land use change also affects groundwater resources. The degree and magnitude of impact will depend on local conditions. In a small Sahelian catchment in Niger, Seguis *et al.* (2004) found that the transition from a wet period under a 'natural' land cover (1950) to a dry period under cultivated land cover (1992) resulted in a 30 to 70% increase in runoff. Recharge in this catchment occurred preferentially through ponds, and thus the increased runoff caused a significant and continuous water table rise over the same period. In this catchment, Seguis *et al.* (2004) concluded that the impacts of land use change were more important than drought.

In a south-western Uganda catchment, clearing of vegetation has led to a 90% reduction in yields from local groundwater springs (Mutiibwa, 2008). The clearing has been driven by population growth and the need to cultivate and settle land. Loss of vegetation cover has resulted in less interception and infiltration of rainfall, and increased runoff. The dominant recharge mechanism is direct infiltration of rainfall and therefore changes in the rainfall-runoff relationship have resulted in a significant reduction in groundwater recharge.

A range of technical and socio-economic factors have contributed to the current condition of groundwater resources, and these will influence their management in the future also. Inadequate information to inform groundwater allocation; lack of qualified personnel; increasing contamination of water resources from agriculture, industries and mining; uncontrolled groundwater abstraction; lack of land use planning; inadequate financial capacity and a lack of education and awareness amongst stakeholders are just some of the challenges that must be overcome (Kalugendo, 2008). Mutiibwa (2008) concluded that the appropriate management of groundwater resources required not only a technical and financial capacity, but also 'political goodwill'.

2.4 Implications for groundwater dependent systems and sectors

Groundwater dependent systems comprise those communities, industries and environments that rely on groundwater for water supply. Dependence on groundwater in developing countries is high, due to either water scarcity or a lack of safe drinking water from surface water supplies. Climate change and other pressures may compromise the availability and quality of groundwater resources with significant implications for human and environmental health, livelihoods, food security and social and economic stability. Degradation of groundwater will also increase the susceptibility of poor communities to extreme events (Ranjan et al., 2006).

2.4.1 Rural and urban communities

Shallow wells often provide an important source of drinking water for rural populations in developing nations. Increased demand and potentially increased severity of droughts may cause these shallow wells to dry up. With limited alternatives for safe drinking water supplies (surface water may be absent or contaminated and deeper wells may not be economically feasible), loss of groundwater would force people to use unsafe water resources or walk long distances for water (Kongola, 2008). This has associated impacts for human health and the capacity (time) to earn an income or gain education.

The livelihoods of rural populations are largely dependent on land, water and the environment with limited alternatives compared to their urban counterparts. Reduced water availability can cause severe hardships. Drying up of pasture and drinking water to livestock can wipe out herds of livestock that are sources of income, family security and food. Small scale irrigation enterprises, usually reliant on shallow groundwater, may also fail (Kongola, 2008). Where increases in heavy rainfall events are projected, floods can wash away sanitation facilities, spreading waste water and potentially contaminating groundwater resources. This may lead to increased risk of diarrheal disease (Taylor *et al.*, 2008). The risk of such contamination is likely to be greater in urban areas due to higher population density and concentration of source pollutants. In coastal regions, sea water intrusion may limit the capacity of communities to cope with already large and rapidly expanding populations (Ranjan *et al*., 2006).

2.4.2 Agriculture

Globally, irrigated agriculture is the largest water use sector (Kundzewicz *et al.*, 2007). In areas where the availability of groundwater is reduced, irrigation may become unviable, particularly if demand for drinking water supply in the area (a higher priority) cannot be met. Alternatively, irrigation may need to occur on an opportunistic basis during periods of water availability or adopt alternative water resources (such as recycled waste water), or technologies and methods for increased water use efficiency. In areas where groundwater availability increases, agriculture may benefit. However shallow rising water tables may also cause problems such as soil salinization and water logging.

2.4.3 Ecosystems

The impact of climate change is likely to accentuate the competition between human and ecological water uses, particularly during periods of protracted drought (Loaiciga, 2003). Environmental implications include the reduction or elimination of stream baseflow and refugia for aquatic plants and animals, dieback of groundwater dependent vegetation, and reduced water supply for terrestrial fauna. In areas where salinization occurs, e.g. coastal regions, salt sensitive species may be lost. Other sources of groundwater contamination may also adversely affect ecosystems.

2.5 Uncertainties and knowledge gaps

Quantifying impacts of climate change on groundwater is difficult and is subject to uncertainties in future climate projections (particularly precipitation) and the relative influence of other factors, e.g. vegetation response to change in carbon dioxide. Studies of climate change impacts on groundwater recharge have largely focused on quantifying the direct impacts of changing precipitation and temperature patterns, assuming other parameters remain constant (Holman, 2006). Few studies have addressed indirect climate effects such as change in land use, vegetation cover and soil properties (Holman, 2006; Jacques, 2006). Natural climate variability is also often ignored with the focus typically being on anthropogenic climate change impacts only.

To focus solely on the direct impacts of climate change arising from temperature and precipitation is to neglect the potentially important role of societal values and economic pressures in shaping the landscape above aquifers (Holman, 2006). To obtain more realistic predictions of hydrological response to the future climate, the impact of indirect consequences of climate changes – such as sea level rise, changes in agricultural practice and land use and the development in water demand for domestic and irrigation purposes – and natural climate variability also need to be addressed. This will require an integrated approach that considers the physical processes as well as describing the plausible human developments in the future (van Roosmalen *et al*., 2007).

There is significant uncertainty in the global recharge mapping (Döll and Flörke, 2005). This is due to uncertainties in projected precipitation and the inability of the Döll and Florke's (2005) recharge modelling to capture preferential recharge from surface water bodies such as streams (Döll and Florke, 2005). Whilst providing an indicator of potentially vulnerable regions, this global mapping in not suitable for assessing vulnerability at national or watershed scales. Information and data at a sub-regional and groundwater basin level are required for operational and investment purposes.

Watershed case studies on global climate change are a matter of concern (Varis *et al*, 2004); however in many locations they will be constrained by a paucity of meaningful data. Many developing nations are data poor, and there are also many uncertainties and limitations associated with downscaling global climate models to this scale. There is a need for better database management and dissemination of information for water resource managers.

Current understanding of climate change impacts is poor. However there are a number of organizations beginning to enhance the understanding of climate change impacts on groundwater resources. This includes UNESCO's initiative Groundwater Resources Assessment under the Pressures of Humanity and Climate Changes (GRAPHIC), with which the International Groundwater Resource Assessment Centre (IGRAC) and the International Association of Hydrogeologists (IAH) Commission on Climate Change are partners. Whilst knowledge of climate change impacts for groundwater is advancing, there does not appear to be any coordinated approach for developing responses (adaptation).

GRAPHIC (2008) discusses additional knowledge and data gaps relevant to groundwater and climate change.

2.6 Groundwater vulnerability to climate change at a World Bank regional scale

A preliminary assessment of the vulnerability of groundwater in World Bank regions to climate change was undertaken to highlight any geographies with particularly low or high vulnerability to climate change. The assessment was developed by the authors using the basic criteria defined below. It assesses vulnerability for 2050 climate change scenarios, assuming all non-climatic conditions as current. The assessment is at regional scale and is intended as a general indicator only. As a high level assessment it might help guide priorities for further work to more precisely assess vulnerability to climate change and to build the resilience of groundwater dependent systems. It is not intended to assess country-scale priorities.

Four criteria were considered in the regional vulnerability indicator assessment (Table 2.2):

- sensitivity: current level of exploitation of groundwater resources – as indicated by the use of groundwater relative to average annual recharge (after IGRAC, 2004);
- exposure: the magnitude and trend in changes in rates of groundwater recharge under 2050 climate change projections (after Döll and Flörke, 2005);
- exposure: the exposure of regional water resources to sea level rise and contamination due to storm surge (based on the authors' assessment of cyclone incidence, the extent of coastal areas in the region and population density in these areas);
- adaptive capacity: wealth, as measured by per capita gross national income (GNI; World Bank, 2008[5])

Groundwater use is used as an indicator of sensitivity to climate change. The second and third criteria were indicators of exposure and GNI was used to indicate adaptive capacity. These factors were combined to provide a vulnerability indicator. Adaptive capacity and the combination of exposure and sensitivity indicators were weighted evenly. Weighting to sea level rise and storm surge risk was reduced to reflect its uneven application to World Bank regions. While there remains significant uncertainty with this assessment, it suggests that groundwater in the World Bank Europe and Central Asia region is the least vulnerable to the effects of climate change. This reflects the relatively low level of utilization of groundwater, the projected increase in rainfall (in many areas), minimal exposure of groundwater to risks from sea level rise and storm surge and higher per capita income. Groundwater resources in the South Asia and Africa regions were considered to be most vulnerable.

Country-to-country differences in vulnerability are expected to be large, with this regional scale analysis most likely masking important 'hot spots' of climate change vulnerability. A country level analysis, using similar criteria, but based on more definitive information is warranted to establish clearer priorities for further work. Such an assessment is beyond the scope of this review.

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[5] Data from http://go.worldbank.org/GKIIAZEJR0

Table 2.2 Preliminary assessment of vulnerability of groundwater in World Bank regions to climate change

	Sensitivity	Exposure		Adaptive capacity	
World Bank region	**Utilization of groundwater**	**Climate change impact on recharge**	**SLR[1] & storm surge exposure**	**Per capita GNI[1]**	**Vulnerability[2]**
East Asia & Pacific	Moderate	Increase	Medium	Moderate	Moderate
Europe & Central Asia	Low	Increase	Low	High	Low
Latin America & Caribbean	Moderate	Reduction	Medium	Moderate	Moderate
Middle East & North Africa	High	Uncertain	Low	Moderate	Moderate
South Asia	Moderate	Negligible	High	Low	High
Africa	Moderate	Reduction	Low	Low	High

1. SLR – sea level rise; GNI – gross national income (in $US)
2. Vulnerability assessed from the sum of average of sensitivity and exposure ratings and adaptive capacity rating.
   - Groundwater utilization – low (2), moderate (4), high (6)
   - Impact on recharge – increase (2), uncertain/negligible (4), reduction (6)
   - SLR exposure – low (1), medium (2), high (3)
   - Per capita GNI – low (6), moderate (4), high (2) – relative to each other

   Low vulnerability (<6), Moderate (6-9), High (>9)

3. Adaptation to climate change

3.1 Introduction

What is adaptation?
Groundwater dependent systems have the capacity to cope with some level of hydrological variability (in quality and quantity or water) without impairment (Figure 3.1) This 'coping range' varies with the sensitivity of the groundwater dependent system to changes in various groundwater attributes (e.g. water quality, depth, pressure, discharge flux). Extremes of natural climatic variability (e.g. prolonged climatic drought) may mean that some groundwater attributes fall outside the coping range of the system, resulting in socio-economic and/or environmental harm. In some areas, human-induced climate change threatens to change the hydrological environment such that its state is outside the system's coping range more frequently, potentially perpetuating that harm (Figure 3.1).

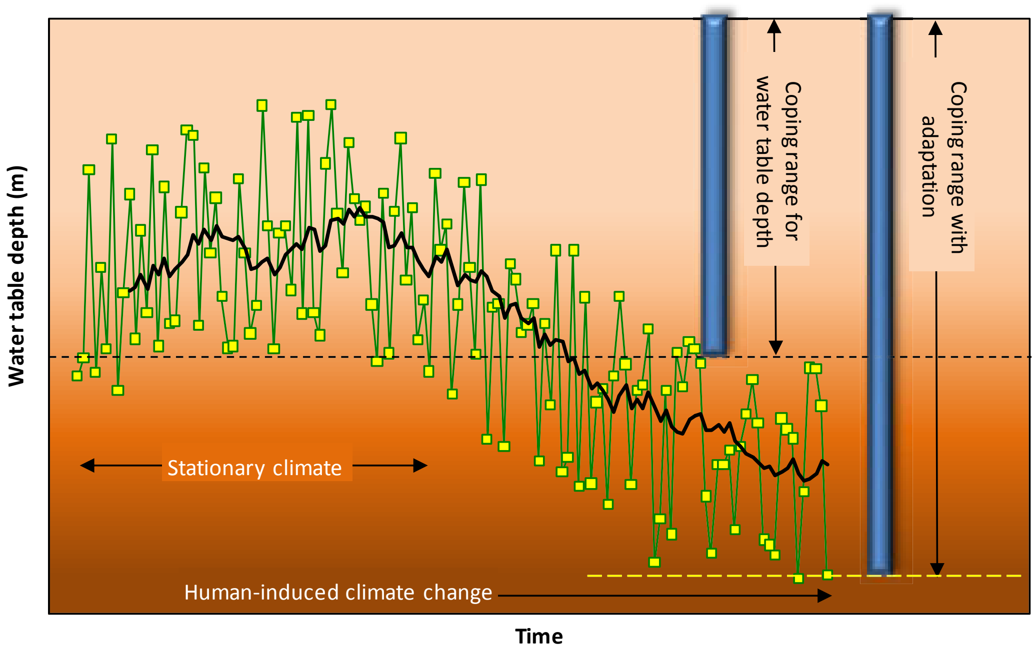

Figure 3.1 Coping range and adaptation to human-induced climate change (redrawn from Willows and Connell, 2003).

The graph shows variation in a hypothetical hydrological parameter (e.g. water level in shallow aquifer) under stationary conditions and human-induced climate change (the solid black line shows the mean state). In sequences of dry years, water levels may fall below the depth of a well or bore (which would define the system's coping range) and some form of harm is experienced. In this example, human-induced climate change is projected to initially result in increased frequency of years during which water levels fall below the level from which water can be extracted. As change progresses, this state becomes permanent. With adaptation (e.g. extending the well or sinking a deeper bore) the system's coping range is extended so that permanent harm is avoided. Note that adaptations are rarely required to respond to a single stimulus, such as in this example.

Adaptations are adjustments made in natural or human systems in response to experienced or projected climatic conditions or their *beneficial* or *adverse* effects or impacts (Smit et al., 2001). In the context of this report (and Figure 3.1) they are concerned with reducing the vulnerability of groundwater dependent systems to climate change and hydrological variability. Adaptations are essentially management responses to risks associated with climate variability and climate change.

Figure 3.2 (from Smit *et al.*, 2000) uses three primary questions to conceptualize climate adaptation: (1) adaptation to what, (2) who or what adapts and (3) how does that adaptation occur? Identification and/or development of adaptations should reflect an understanding of these three components. Prior to use or implementation, adaptations should also be evaluated to determine whether they are fit-for-purpose and cost-effective. Adaptations to climate change and variability must also complement or include adaptations to non-climate pressures or conditions that may affect the system.

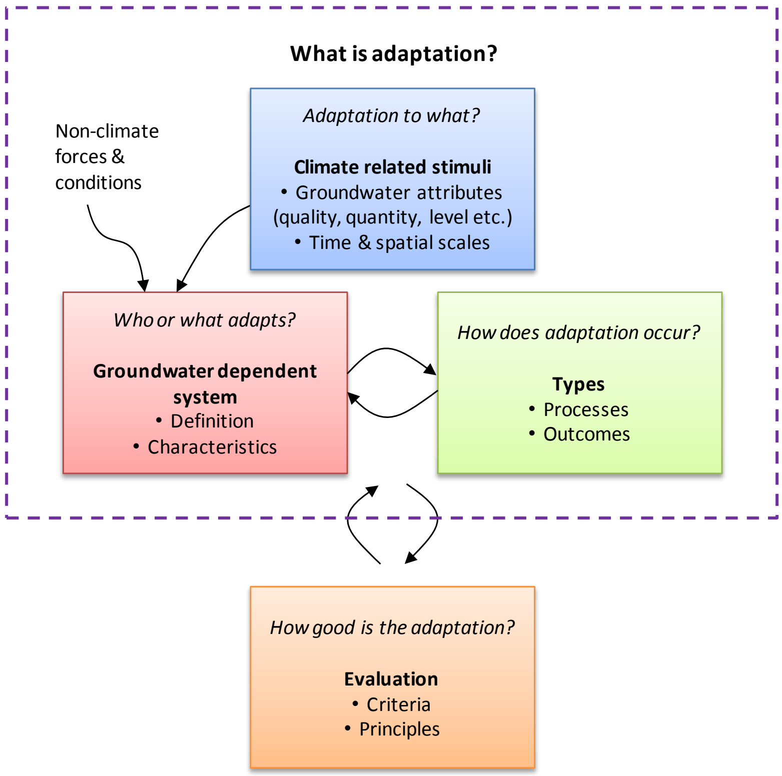

Figure 3.2 Conceptualization of adaptation of a groundwater dependent system to climate change and variability (redrawn from Smit et al., 2000).

Adaptation may occur as the result of planned action (e.g. Figure 3.2) or autonomously. Natural and human systems that are periodically challenged by climatic and hydrological extremes tend to adapt to minimize harm if challenged again in future. Planned adaptation is a pre-emptive response based on an assessment of future climate and hydrological risks.

Forms of adaptation

Burton (1996) developed a useful typology of climate change adaptation options (Figure 3.3), in which he proposed eight broad types, which fall into five groups of risk responses, as follows:

- Accept the risks – in which climate risks are accepted and no action is undertaken to change the exposure or (direct) sensitivity of the system to them. On those occasions when the system's coping range (Figure 3.1) is approached or exceeded, the associated losses are either borne (#2 in Figure 3.3) by those directly exposed or shared (#1 in Figure 3.3) among a broader group. Insurance is an example of the latter. Bearing the loss is a form of adaptation that would typically only apply when losses are either small in relation to the cost of other forms of adaptation or when they cannot be avoided (e.g. loss of ice cover in montane areas subject to increased temperature).

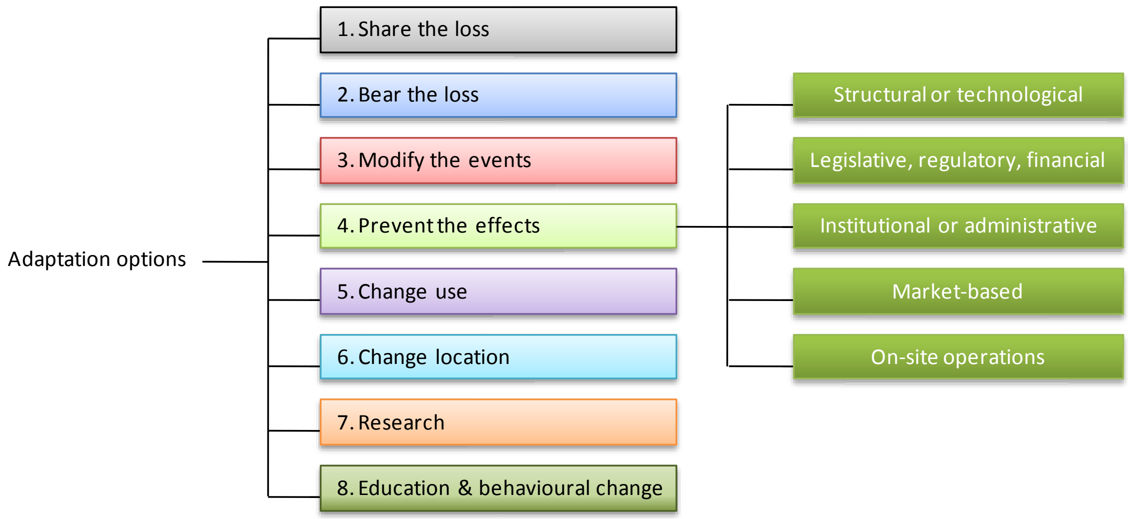

Figure 3.3 Classification of adaptation options (redrawn from Burton, 1996).

- Modify the likelihood of (or exposure to) a climate or related hazard (#3 in Figure 3.3) – in which actions are undertaken to reduce the frequency of events that take the system outside its coping range. In the example illustrated in Figure 3.1 this could include actions that increase groundwater recharge (e.g. vegetation cover change, artificial recharge) to maintain groundwater levels within the range accessible to the well or bore.
- Modify the consequences of (or sensitivity to) a climate or related hazard – in which actions are undertaken to extend the coping range of the system and prevent adverse impacts (#4 in Figure 3.3). The case from Figure 3.1 Figure extending the well to a greater depth to maintain access to water is one example of this type of adaptation. In addition to physical works and measures, this type of adaptation may include changes in institutional or regulatory arrangements and establishment of markets (Figure 3.3).
- Avoid the risk – by either changing the sensitivity (#5 in Figure 3.3) or exposure (#6 in Figure 3.3) of the system to climate risks. For a groundwater dependent system, the former may involve reducing the reliance of the system on irrigation by, for example, moving from a perennial crop that must be irrigated every year to an annual one that is grown opportunistically, when water is available. The latter option may involve moving irrigated cropping to another location with a more reliable water supply.
- Build adaptive capacity – undertake research (#7 in Figure 3.3) to better understand the risks faced, the system's vulnerability to climate change and hydrological variability and/or improve or extend the range of adaptations. Education and behavioural change programs (#8 in Figure 3.3) could be developed and implemented to improve stakeholders' and communities' understanding of risks and management responses. Such campaigns might also empower groups to develop new adaptations or apply existing adaptations (across types #3-5 in Figure 3.3) more effectively or extensively.

All of these types are applicable to the groundwater vulnerability assessment framework. Acceptance of risk may be the adaptation choice in the first pass of the vulnerability assessment (Figure 3.1), in situations where there is low vulnerability or where there is no meaningful prospect of avoiding an impact (or consequence) should the adverse climate or hydrological state be realized. Other options would be considered in the second pass of the vulnerability assessment process.

3.2 Adaptation options for risks to groundwater dependent systems from climate change and hydrological variability

This section contains a review of adaptation options for risks to groundwater dependent systems from climate change and hydrological variability. It is structured around the five groups of options discussed in the previous section, where they are appropriate and five main groundwater process themes (Figure 3.4):

- Managing groundwater recharge
- Protection of groundwater quality
- Managing groundwater discharge
- Management of groundwater storage
- Managing demand for groundwater

In most instances, 'accept the risk' options (#1 and #2 in Figure 3.3) are limited or need not be specified. These options are mostly likely to be considered where risk is low relative to the cost of adaptation or where other forms of adaptation are unlikely to be effective in mitigating risk.

Many of the options that fall within the 'building adaptive capacity' group are cross-cutting and at least partially apply to multiple themes. These are introduced in a separate section (below), preceding the discussion by groundwater themes. Applicable adaptive capacity adaptations are also listed for the various groundwater themes. Adaptation options in this section are relevant under situations in which climate change and hydrological variability reduce the security of groundwater supply and increase the vulnerability of the water-dependent system. In contrast, Section 3.3 deals with adaptations to situations in which climate change is projected to result in groundwater recharge and/or discharge increasing to the point of adverse impact on a water-dependent system.

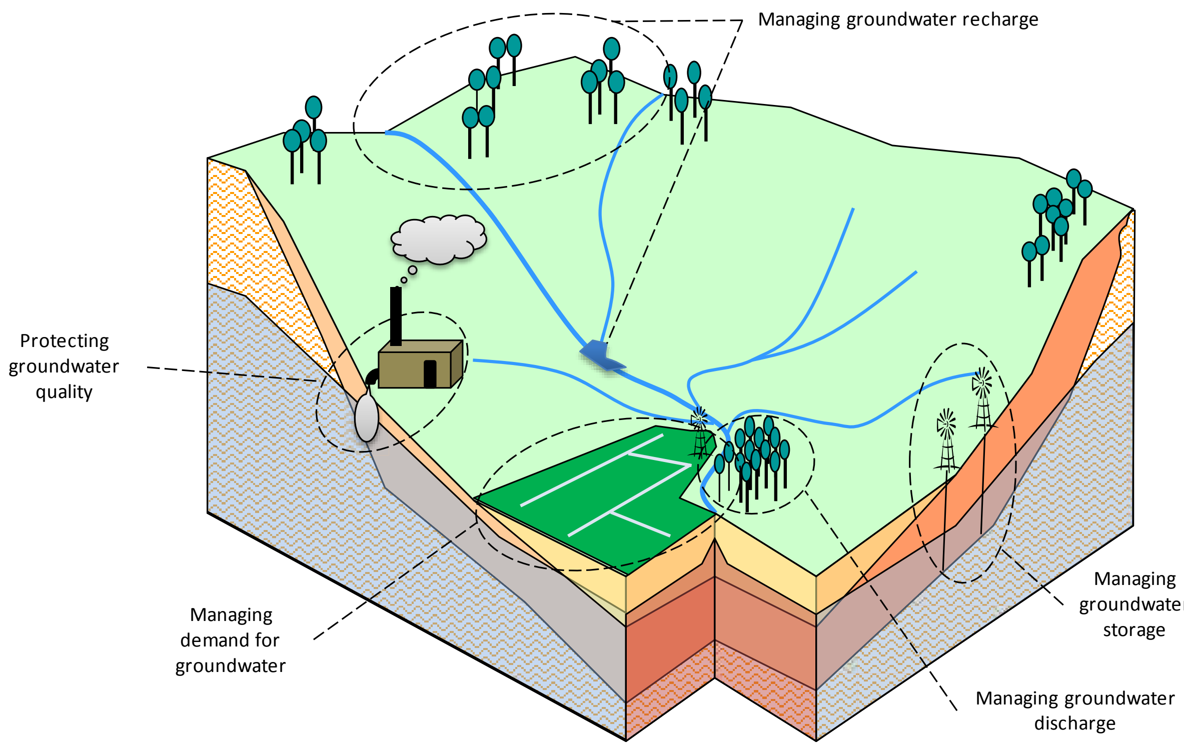

Figure 3.4 Groundwater adaptation options, based on groundwater processes and location in the landscape.

3.2.1 Building adaptive capacity for groundwater management

Adaptive capacity building options are generally concerned with providing the necessary conditions for other forms of adaptation to be implemented successfully, rather than managing or avoiding climate or hydrological risks directly. They fall into several categories, as noted in section 3.1 (Table 3.1).

Table 3.1 Adaptation options: building adaptive capacity

Adaptation option group	Adaptations
Social capital These options are concerned with enabling communities to understand climate and hydrological risks and actively participate in management responses.	• Education and training – to improve community and stakeholder understanding of climate risks and their capacity to participate in management responses and/or generate, modify or apply adaptations. • Governance – devolve some level of responsibility for planning and management of groundwater to local communities to increase local 'ownership' of problems and responses • Sharing information – instigate processes for sharing of information regarding climate risks and responses within and between vulnerable communities.
Resource information Gathering and providing information on climate risks and the groundwater system being managed.	• Understanding climate – analysis of historical and palaeoclimate information to understand the natural drivers of climate variability and links between interannual to interdecadal climate modes (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation) and climate risks. Development of historical and synthetic climate datasets for climate impact studies. • Climate change projections – developing downscaled climate change projections for the area of interest. • Quantify the groundwater system – understand the scale and characteristics of the aquifer(s); recharge, transmission and discharge processes; water balance (including use); water quality etc. • Monitoring, evaluation and reporting – of the state of the groundwater resource, level of use, vulnerability to various threatening processes and effectiveness of climate and other adaptations.
Research & development Research and development activities to improve the effectiveness of adaptive responses to climate change and hydrological variability.	• Climate impact assessments – studies to better define the nature of projected climate change impacts on the groundwater system and the associated climate and hydrological risks. • Management of groundwater recharge – methods to enhance groundwater recharge and water availability. • Management of groundwater storage – technologies, water management and other practices to maximize groundwater storage capacity and resource availability. • Protection of water quality – technologies and management systems to enable treatment and reuse of contaminated water and avoid contamination of higher quality water by water of lesser quality. Protection of island and coastal aquifers from effects of sea level rise. • Managing demand for groundwater – technologies and management practices that: improve the efficiency of urban and agricultural uses of water; reduce water quality requirements of non-potable uses; or reduce the need for water. • Management of groundwater discharge – land management practices to reduce unwanted discharge of groundwater (especially) by non-indigenous woody vegetation. • Markets – improved arrangements for operation of markets for water and related environmental services. • Governance and institutional arrangements – improved methods for governance and stewardship of groundwater resources.

Adaptation option group	Adaptations
Governance & institutions Improving governance and institutional arrangements for groundwater resource management. Improved planning regimes for groundwater and associated human and natural systems.	• Conjunctive management of surface water and groundwater in rural areas. Integrated water cycle management (including various potable and non-potable sources in urban areas). • Multi-jurisdictional planning and resource management arrangements for large scale aquifer systems that cross jurisdictional boundaries. • Defining water allocations based on resource share rather than volume. • Set and regulate standards for (e.g.) groundwater resource and land use planning, water governance, environmental management, water quality, resource information, water use efficiency (in agricultural, industrial and urban settings). • Set and enforce a cap on level of utilization of groundwater within a management unit. Cap should be based on the defined sustainable yield (accounting for robust understanding of climate risks and environmental water requirements of groundwater-dependent ecosystems [GDEs]) unless there is to be planned mining of an historical groundwater resource. Cap and water allocations to be reviewed and reset periodically to account for changed management and development objectives and changes in climate and resource availability. • Human needs water reserve – secure allocation of groundwater to meet basic human needs in groundwater dependent communities. • Environmental water reserve – secure allocation of groundwater to meet requirements of GDEs. • Measurement and public reporting of groundwater use. • Drought response planning.
Markets Establishment and operation of markets for water and associated environmental services.	• Markets – establishment and operation of markets for and trading of water within a groundwater system. Market to determine the price for water. • Property rights – establish clear title and property rights to groundwater. • Include generation of recharge and surface water flows in water markets to enable payments by water users to owners and managers of land generating water of appropriate quality.

3.2.2 Managing groundwater recharge

Groundwater recharge areas may be managed to protect or enhance water resources and to maintain or improve water quality. While the latter is also covered in section 3.2.3 it is relevant here as activities in groundwater recharge areas that lead to groundwater contamination also reduce resource availability. Potential adaptations are outlined in Table 3.2.

3.2.3 Protecting groundwater quality

Climate change and hydrological variability may affect the quality of groundwater available for use in a groundwater dependent system. This is particularly true of groundwater resources on small islands and coastal areas that are projected to be subject to sea level rise. It is also true where reduced security of supply leads water resource managers to include lower quality water in the supply stream (e.g. through MAR using storm water or treated waste water) or where increased pressure on groundwater resources leads to increased use and greater risk of contamination of a high quality aquifer by any overlying or underlying poorer quality aquifers. Adaptation options are outlined in Table 3.3.

Table 3.2 Adaptation options: managing groundwater recharge

Adaptation option group	Adaptations

Modify exposure to climate risk (#3)	• Manage or reduce the level of woody vegetation cover to optimize groundwater recharge (while protecting ecological values and avoiding erosion etc.).
	• Managed aquifer recharge (MAR; or other forms of artificial recharge) in/near urban and rural settings to capture and use:
	  • urban storm water, including use of detention ponds and infiltration systems;
	  • treated wastewater from industrial facilities and urban wastewater treatment plants;
	  • overland flows – (e.g.) via capture in dams that are designed to leak and recharge water tables;
	  • river flows
	• Adjust land management practice in groundwater recharge areas to maximize water table recharge and reduce overland flows – for example through maintaining ground cover, contour banks, Keyline farming systems etc.
	• River regulation to maintain flows over recharge beds for alluvial aquifers.

Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	• Land use planning controls that limit industrial forestry plantation development in key recharge areas. • Land use planning and environmental management controls to avoid development of industrial or other facilities, in key recharge areas, that pose high risk of aquifer contamination.
Build adaptive capacity (#3-#5, #7)	• Land use planning and environmental management controls to regulate developments in key recharge areas that increase vulnerability of groundwater system. • Water allocation policy framework that incorporates impacts of land use on groundwater recharge and generation of surface flows. Land use changes with high water requirements required to purchase entitlement to intercept groundwater recharge or surface flow.

Note: # refers to the adaptation option type in Figure 3.3.

3.2.4 Managing groundwater storages

While aquifers are recognized as underground water storages, they are rarely operated with the same level of precision and control as major surface water storages. Opportunities exist (Table 3.4) to manage groundwater storages more effectively, and reduce the vulnerability of systems that depend on them to climate change and hydrological variability.

3.2.5 Managing demand for groundwater

Climate change adaptations for water resources most frequently operate on demand management. In many cases, the adaptations for groundwater dependent and surface water dependent systems will be identical. Options are outlined in Table 3.5.

In areas where climate change reduces supply security for surface water resources, it is likely that there will be increased focus on utilization of groundwater resources *as an adaptation to climate change*. This will require greater attention to management of demand for groundwater and for conjunctive management with surface water. It may also be possible to use groundwater as a store for surplus surface water flows during periods of abundant supply for use during periods of surface water scarcity.

Table 3.3 Adaptation options: protecting groundwater quality

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	• Regulate surface water and groundwater levels in rivers, lakes and surface water storages and shallow water table areas with potential acid sulfate soils to avoid activation and acid contamination of surface waters and groundwater. • Construct bore fields in coastal aquifers to drawdown the salt water aquifer and protect freshwater from incursion as sea levels rise. • Use MAR or other forms of artificial recharge of freshwater to coastal aquifers – to maintain heads in freshwater and protect aquifer from incursion by salt water as sea levels rise. • Manage utilization/drawdown of groundwater to avoid contamination of higher quality groundwater by poor quality water in overlying or underlying systems.
Modify sensitivity to climate risk (#4)	• Treatment of low quality water (e.g. desalination, filtration) to a standard appropriate for particular uses.
Avoid risk (#5, #6)	• Land use planning and environmental management controls to avoid development of industrial or other facilities that pose high risk of contaminating important water resource aquifers.
Build adaptive capacity (#3-#5, #7)	• Research to define sustainable yield and quality of aquifer systems – to ensure adequate water quality maintained. • Land use planning and environmental management controls to regulate developments that pose a high risk of contamination to aquifers. • Education and behavior change campaign, with appropriate monitoring and regulatory support, to emphasize avoidance of contamination of water resource aquifers industrial facilities, fuel or other chemical storages, etc. • Research to develop water treatment processes that are less expensive and require less energy. • Develop water quality standards that can be applied to different uses. Supply water to meet these standards.

Note: # refers to the adaptation option type in Figure 3.3.

Table 3.4 Adaptation options: managing groundwater storages

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	• Increase storage capacity in aquifers - through hydrofracturing, dissolution (in karst systems) or pressurization of cavities. • Increase storage availability in aquifers prior to expected periods of high recharge. • MAR and other forms of artificial recharge to maximize use of available water and storage capacity in aquifers. • Re-inject water from mine dewatering operations into aquifer down-gradient of mine (where of useful quality) rather than run to waste.

Adaptation option group	Adaptations
Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	*No options applicable*
Build adaptive capacity (#3-#5, #7)	• Research and/or resource assessments to improve understanding of aquifer properties and define opportunities and management practices for more effective storage management. • Develop technical and analysis skills in groundwater resource managers to operate aquifers as groundwater storages. Develop monitoring infrastructure to support such management. • Develop seasonal and longer term forecasting/projection of groundwater resources based on well developed understanding of main climate drivers for aquifer. Base seasonal and long-term allocations on understandings of water availability.

Note: # refers to the adaptation option type in Figure 3.3.

3.2.6 Management of groundwater discharge

Aquifer systems discharge water to the land surface, rivers, lakes, wetlands or to near or off-shore marine environments. Discharge, recharge and utilization are in a state of dynamic equilibrium, such that changes in recharge or utilization ultimately result in a change in discharge. In some settings, it is possible to increase resource availability (for use by human systems) by reducing groundwater discharge. Potential climate change adaptation options relating to management of groundwater discharge are outlined in Table 3.6.

3.3 Managing for increased groundwater recharge

While it is the case that the latest climate change projections (IPCC, 2007) suggest a worsening of water security in many nations, this is not always the case. Kundzewicz et al. (2007; for surface water flows) and Döll and Flörke (2005; for groundwater; Figure 2.2) present data that projects increase surface flows and groundwater recharge under some emissions scenarios. Areas projected to have increased recharge include some where water is currently in short supply (e.g. parts of the Sahel region of Africa, parts of the Arabian Peninsula, north-east China) and others (e.g. Siberia) where it is not.

Increased rainfall and recharge in some areas may, other factors being equal, lessen the vulnerability of groundwater dependent systems. However it is conceivable that in some locations, increased recharge associated with changes in climate and hydrological variability may make some aspects of such systems more vulnerable. Such circumstances include, for example, hydrogeological settings in which increased recharge results in the development of shallow water tables and salinization of land and water resources (such as has occurred in parts of southern Australia in response to the replacement of native woody vegetation with agricultural crops and pastures; NLWRA, 2001) or geological instability.

Potential options for adapting to increased groundwater recharge are outlined in Table 3.7.

Table 3.5 Adaptation options: managing demand for groundwater

Adaptation option group	Adaptations
Accept the risk (#1, #2)	• Crop insurance for drought-related crop or livestock production failures. • Welfare or related support payments to primary producers experiencing drought-related crop or livestock production failures
Modify exposure to climate risk (#3)	• Effectively cap artesian bores to reduce or eliminate wastage. • Use pipes or sealed channels to distribute water from groundwater pumps and/or artesian bores to point of use to reduce or eliminate waste from seepage or evaporation. • Use or improved use of seasonal forecasts and water allocation projections in crop selection and decisions on area to irrigate. • Maintain water reticulation systems (where they exist) to reduce leakage and wastage. Apply appropriate standards of construction and materials to water supply systems to reduce losses. • Develop system of water restrictions to apply to domestic and industrial consumption during periods of supply scarcity. • Secure and maintain environmental water provision for groundwater dependent ecosystems. • Substitute use of high quality groundwater for lower quality groundwater or water from other sources (e.g. treated waste water) as appropriate to the use. • Use MAR to 'bank' groundwater for use during periods of scarcity of surface water supplies.
Modify sensitivity to climate risk (#4)	• Measure use of groundwater. • Improve on-farm efficiency of water use – e.g. control deficit irrigation (where appropriate to crop), improved irrigation scheduling, use of more efficient application methods (i.e. sprays, drip irrigators or underground irrigation rather than flood, furrow or overhead sprinklers). • Select crops with lower water requirements and/or higher value per unit of water required. • Achieve balance of perennial horticulture (with high sensitivity to water shortage) and opportunistically irrigated annual crops in order to match water use with the projections of water resource availability. • Substitute irrigation production for dryland agriculture to the extent required by the level of irrigation supply.
Avoid risk (#5, #6)	• Land use planning to limit urban and/or agricultural development to levels consistent with current and projected water supply availability.
Build adaptive capacity (#3-#5, #7)	• Conjunctive management of surface water and groundwater in rural areas. Integrated water cycle management (including various potable and non-potable sources in urban areas). • Water allocation framework for groundwater use that limits allocations to sustainable yield (unless there is planned depletion of historical reserves). Water allocations to be reviewed and reset periodically to account for changed management and development objectives and changes in climate and resource availability • Multi-jurisdictional planning and resource management arrangements for large scale aquifer systems that cross jurisdictional boundaries.

Adaptation option group	Adaptations
	• Set and regulate standards for (e.g.) groundwater resource planning, water governance, environmental management, water quality, resource information, water use efficiency (in agricultural, industrial and urban settings). • Development and implementation of economic tools (for example pricing/charges/tariffs for groundwater within an aquifer system). Pricing to reflect demand and any costs of supply and treatment. Where appropriate, more complex economic markets could be established. • Defining water allocations based on resource share rather than volume. • Water resource managers to provide early advice to irrigators on water allocations. • Human needs water reserve – secure allocation of groundwater to meet basic human needs in groundwater dependent communities. • Environmental water reserve – secure allocation of groundwater to meet requirements of GDEs. • Measurement and public reporting of groundwater use. • Research to develop more water efficient irrigation and agricultural production systems and crops. • Education and behavior change campaign to increase adoption of existing (and any new) adaptations for agricultural water use efficiency. • Education and behavior change campaign to raise awareness of water conservation issues and practices and change attitudes and behaviors. • Community-level participation in water resource planning processes, especially for irrigation. • Stepped pricing structure for domestic and industrial water use – with price per unit volume increasing in multiple steps as consumption extends beyond basic needs.

Note: # refers to the adaptation option type in Figure 3.3.

Table 3.6 Adaptation options: managing groundwater discharge

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	*No options applicable*
Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	• Avoid or limit establishment of industrial forestry plantations or other deep-rooted, high water use species in areas with shallow, fresh groundwater that is used for other purposes.
Build adaptive capacity (#3-#5, #7)	• Land use planning controls that enable restrictions on the extent to which high water use species are established in areas with shallow, fresh groundwater that is used for other purposes. • Market mechanisms that account for groundwater uptake by land uses (e.g. forestry plantations) in a consistent way with other direct uses of groundwater.

Note: # refers to the adaptation option type in Figure 3.3.

Table 3.7 Adaptation options: managing increased groundwater recharge

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	• Change land use or management to increase woody or other higher water use vegetation cover. • Establish deep rooted vegetation in areas subject to instability if seasonally water-logged. • Construct surface or sub-surface drainage in discharges to intercept groundwater and drain to appropriate location (e.g. stream for fresh water, evaporation basin for saline water). • Groundwater pumping to hold water table at a safe depth in the vicinity higher value agricultural or environmental assets and population centers. • Increase use of groundwater for irrigation or other purposes.
Modify sensitivity to climate risk (#4)	• Establish high water use vegetation in groundwater discharge areas (that are adapted to soil and water salinity) to increase groundwater discharge. • Establish salt tolerant vegetation (with commercial use in grazing or cropping) in salinized, shallow water table areas.
Avoid risk (#5, #6)	*No options available*
Build adaptive capacity (#3-#5, #7)	• Research and development to introduce farming and other management systems that reduce the vulnerability of natural and human systems to the consequences of increased recharge.

Note: # refers to the adaptation option type in figure 3.3.

3.4 Examples of adaptation to climate change and hydrological variability from developing countries

3.4.1 Managed aquifer recharge

Managed aquifer recharge (MAR) involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. It forms one of the 'managing aquifer recharge' adaptation responses listed in Table 3.2 and is increasingly being considered as an option for improving the security and quality of water supplies in areas where they are scarce (Gale, 2005).

MAR is among the most significant adaptation opportunities for developing countries seeking to reduce vulnerability to climate change and hydrological variability. It has several potential benefits, including: storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.

Implementation of MAR requires suitable groundwater storage opportunities. Falling water levels or pressures in aquifers in many regions throughout the world are creating such opportunities, either as unsaturated conditions in unconfined aquifers or as a pressure reduction in confined aquifers. However, MAR is not a remedy for water scarcity in all areas. Aquifer conditions must be appropriate and suitable water sources (e.g. excess wet season surface water flows or treated waste water) are also required. MAR potential should be determined in any particular country or region before activities commence.

MAR may not succeed as a stand-alone adaptation to scarcity of groundwater supply. Its implementation should also be accompanied by demand management (Table 3.5) and capacity building (Table 3.1) measures. Without these MAR may fail, particularly where aquifers are overexploited or where poor selection of the MAR site and/or type occurs due to lack of appropriate knowledge (Dillon, pers. comm., 2008).

MAR methods may be grouped into the following broad approaches (Figure 3.5):

- Spreading methods – such as infiltration ponds, soil-aquifer treatment, in which overland flows are dispersed to encourage groundwater recharge;
- In-channel modifications – such as percolation ponds, sand storage dams, underground dams, leaky dams and recharge releases, in which direct river channel modifications are made to increase recharge;
- Well, shaft and borehole recharge – in which infrastructure are developed to pump water to an aquifer to recharge it and then either withdraw it at the same or a nearby location (e.g. aquifer storage and recovery, ASR);
- Induced bank infiltration – in which groundwater is withdrawn at one location to create or enhance a hydraulic gradient that will lead to increased recharge (e.g. bank filtration, dune filtration)
- Rainwater harvesting – in which rainfall onto hard surfaces (e.g. building roofs, paved car parks) is captured in above or below ground tanks and then allowed to slowly infiltrate into soil.

There are several common operational issues experienced by MAR schemes (Gale, 2005). These include: clogging of wells, stability of infrastructure under operating conditions, protection of groundwater quality, operation and management of the scheme, ownership of the stored water, monitoring, loss of infiltrated/injected water, policy and cultural acceptability and related stakeholder communications. Successful operation requires appropriate training for operators, access to successful demonstrations of the technologies being deployed and sound and integrated management of water resources[6].

Detailed planning and assessment are required to determine whether MAR is a viable adaptation option. This may be carried out a national and watershed scale. Three fundamental planning steps should be considered:

- Water availability – assess the availability and quality of excess wet season surface water flows or other potential sources. The frequency and volume of availability of suitable water must be assessed for each planning region, as must the influence of natural climate variability and projected human-induced change.
- Evaluate the hydrogeological suitability of the MAR site or region – which largely depends on ease of injecting and recovering the water, the aquifer storage capacity and the aquifer's resistance to clogging.
- Feasibility - the costs, benefit and feasibility of constructing and operating a MAR scheme, including those associated with transporting the recovered MAR water to demand centers needs to be determined.

MAR will not be appropriate in some hydrogeological settings and for some classes of water. Various MAR options exist and are appropriate to parts of at least some World Bank regions.

MAR example: sand dams in Kenya

Sand dams are made by constructing a wall across a riverbed, which slows flash floods/ephemeral flow and allows coarser sediment to settle out and accumulate behind the dam wall. The sedimentation creates a shallow artificial aquifer which is recharged both laterally and vertically by stream flow (Gale, 2005).

Since 1995, over 400 sand dams have been constructed in the Kitui District of Kenya, supported by the SASOL Foundation (Figure 3.6; Foster and Tuinhof, 2004). Each of these dams provides at least 2 000 m^3 of storage and has been constructed by local communities using locally available material. The benefits identified through this program include: water supplies more readily available in the dry season, enhanced food security during drought periods, and less travel time to obtain water supply.

Sand dams are not appropriate for all locations. They require unweathered and relatively impermeable bedrock at shallow depth; the dominant rock formation in the area should weather to coarse, sandy sediments; sufficient overflow is required for fine sediments to be washed away; and risk of build-up of soil and groundwater salinity needs to be low. Cooperative effort, ownership and ongoing maintenance by the local community are also necessary for the success of these schemes (Foster and Tuinhof, 2004).

[6] An IAH (International Association of Hydrogeologists) Commission on MAR are currently working with UNESCO to provide information and education resources about MAR, see: www.iah.org/recharge/.

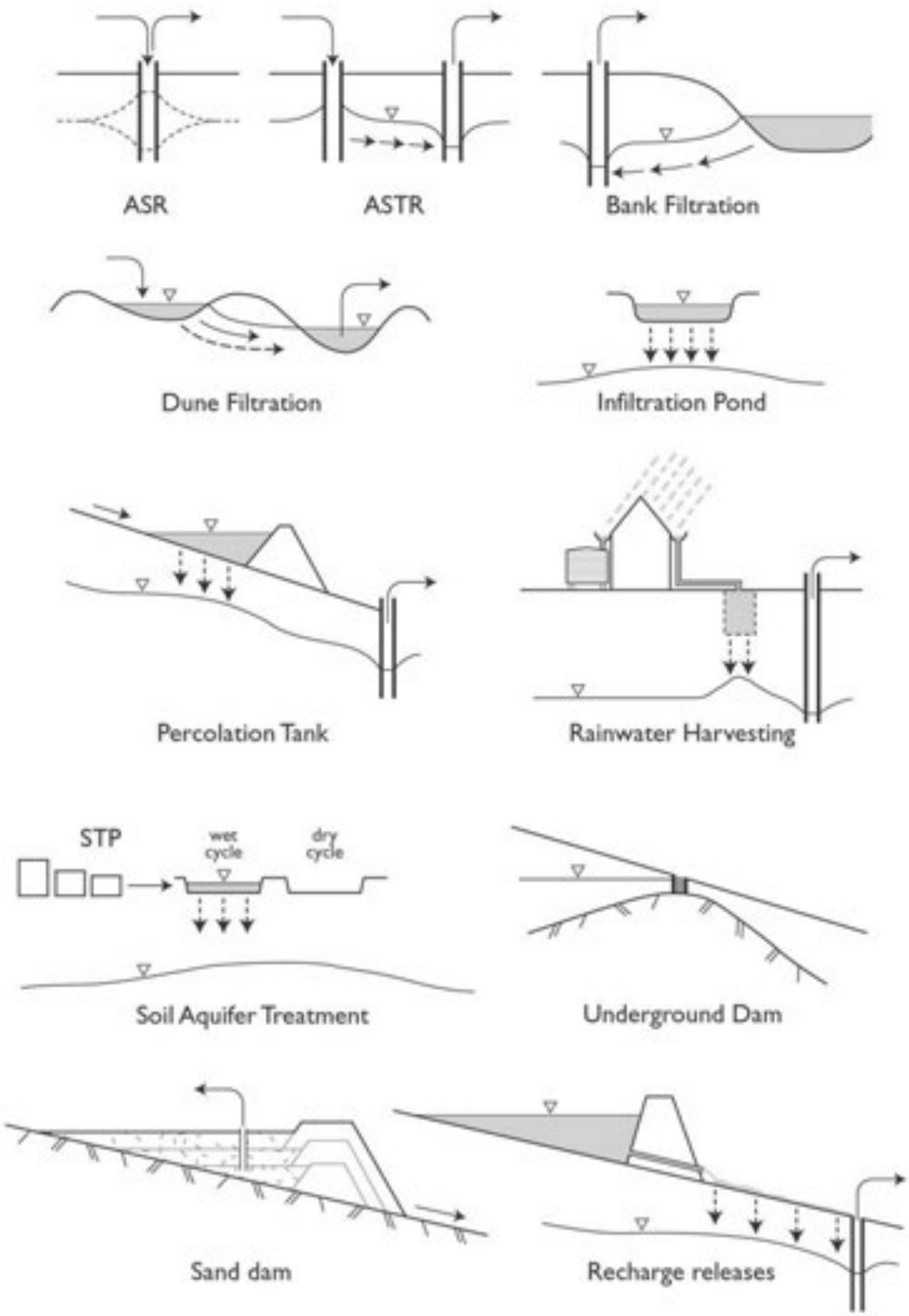

Figure 3.5 Examples of managed aquifer recharge (MAR) approaches.

ASR: aquifer storage and recovery; ASTR: aquifer storage, treatment and recovery, STP: sewage treatment plant. Source: Peter Dillon (pers. comm., 2008)

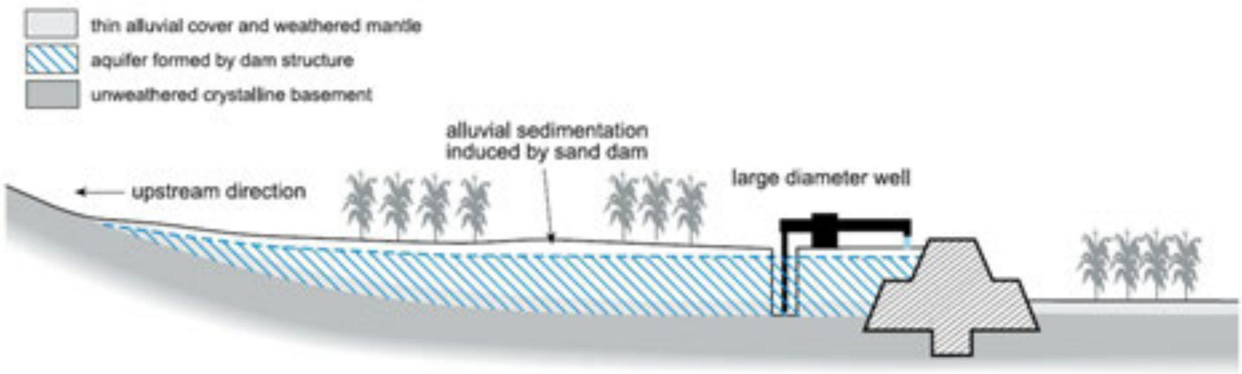

Figure 3.6 Cross section of sand dam structure (from Foster and Tuinhof, 2004)

3.4.2 Groundwater protection: adaptations and challenges for a low atoll

Thin lenses of fresh groundwater floating over seawater comprise the major source of water supply in many atolls. Limited land area, permeable soils and limited vertical relief constrain surface water storage and availability (White *et al.*, 2007). Fresh groundwaters in these environments are becoming increasingly vulnerable, threatened by sea level rise, drought, increasing populations and land use change.

White *et al.* (2007) examined the impact of both ENSO-related droughts and human influences on freshwater availability, and assessed potential adaptation strategies to protect water resources and reduce risks for the densely populated central Pacific atoll, Tarawa, Republic of Kiribati. Whilst focused on an atoll environment, the findings from this work are applicable to many island and coastal regions, and the principle of recharge zone protection is common for all areas where fresh groundwater is available.

Water supply for Tarawa's reticulated system is extracted from freshwater lenses in groundwater reserves. During drought periods, almost all rainwater tanks are exhausted, the thickness of the fresh groundwater lens decreases, many domestic wells become saline and saline groundwater causes the death or severe dieback of mature bread-fruit trees. However, provided pumping occurs at a sustainable rate, large freshwater lenses have historically survived through extended droughts with only moderate increases in salinity.

In order to preserve the freshwater resource and supply for drought periods in Tarawa, it is critical to reduce contamination risk to groundwater. Whilst traditional practices in low-density populations have evolved to minimize contamination risk – for example, defecation on beaches down-gradient from recharge areas and keeping pigs in pens in groundwater discharge zones – these are often in conflict with contemporary land use trends and behavioural patterns. In particular, the keeping of pigs and market gardens in groundwater source areas provide contamination problems for Tarawa.

Historical adaptation measures have been applied with limited success. Installation of reverse osmosis desalination units during previous drought periods failed due to intermittent power supplies, lack of training, and maintenance and operational costs (estimated at 16 times that of groundwater extraction). There has been mixed success for declaring privately owned land in groundwater recharge areas as water reserves with restricted land uses; often the restricted rights of affected landowners has resulted in conflict. Poor access to information regarding available water storage and the impacts of climate variations has also made it difficult to establish water policies and legislation.

Proposed future adaptation strategies for Tarawa broadly fall under three themes: capacity strengthening, demand management and refurbishment of infrastructure and protection and supplementation of freshwater resources. Specifically, these include:

- Establishing a sound institutional basis for the management of water and sanitation;
- Improving community participation in water and related land management planning to reduce conflicts;
- Increasing capacity to analyze and predict extreme water events (especially droughts);

- Improving knowledge of available water resources, including their quality and demand upon them.
- Improving water conservation and demand management strategies and reduce leakage from water supply infrastructure;
- Protecting groundwater source areas from contamination.

White et al. (2007) conclude that improving and sharing knowledge about climate and water resources is an essential element of adaptation and that this knowledge must be communicated in a way that is consistent with traditional oral forms of knowledge transfer. They also highlight the need for investment in regional solutions, local engagement and long-term partnerships.

3.5 Discussion

3.5.1 Avoiding adaptation decision errors

Decisions to apply climate change adaptations are made in an uncertain environment. Even so, decision makers need to consider the risks associated with the future being different to that projected or to the adaptation options not performing as well as expected (Willows and Connell, 2003). Three broad types of adaptation error are recognized:

- Under-adaptation – which is likely to result from situations in which climate change should have been an essential component of a decision, but was either ignored or given less weight relative to other factors than it should have. Such situations are likely to result in insufficient weight being given to climate change adaptation
- Over-adaptation – which results from the inverse of conditions associated with under-adaptation. The importance of climate change risks is overstated relative to other factors and greater emphasis than was necessary is placed on adaptation.
- Mal-adaptation – in which actions are taken which reduce the options or ability of decision makers to manage the impacts of climate change.

Given the uncertain decision-making environment for climate change adaptation, it is necessary to balance the risks of under- and over-adaptation. In the first instance, ‘no regrets’ adaptations, which make sense even in the absence of experienced climatic change, should be deployed. Beyond that, the level of investment in adaptation will depend on the resources available and the severity of consequences and likelihood of various climate change impacts. Where potential impacts are severe and resources are available, the risk and implications of under-adaptation may be too great to bear.

The concept of mal-adaptation should also be extended to include actions that either conflict with other social, economic, resource management or environmental objectives or add further pressure to the global climate system by significantly increasing greenhouse gas emissions. Examples could include:

- clearing native vegetation to increase recharge to aquifers – this would result in emissions of greenhouse gases and loss of biodiversity and could lead to erosion and increased flash-flood risk;
- increasing water availability through treatment of low quality water using expensive and energy intensive processes which will be operated using coal-fired power stations;
- introduction of market-based measures for water resource management that impoverish, or further impoverish small irrigation producers.

3.5.2 Evaluation of adaptation options

The need to avoid the adaptation decision errors described in the previous section suggests some form of evaluation process prior to implementation. Drawing on work carried out for the IPCC, Dolan *et al.* (2001) identified several possibilities, including benefit-cost analysis, cost-effectiveness analysis, risk benefit analysis, multi-objective analysis and multiple criteria evaluation. They also applied a Multiple Criteria Evaluation (MCE) or Multi-Criteria Analysis (MCA) to evaluate a set of adaptation options applicable to Canadian agriculture. The criteria used included:

- Effectiveness
- economic efficiency
- flexibility
- institutional compatibility

- farmer implementability
- independent benefits[7]

The criteria appear to be broadly suited to the evaluation of adaptations in other economic or social sectors, including groundwater resource management. However, 'farmer implementability' would need to be amended to the more generic 'implementability'.

The evaluation anticipated by the vulnerability assessment process (described in the larger report) is against criteria framed around management and development (or other) objectives for the groundwater system. It is anticipated that these would have social, economic and environmental dimensions. Effectiveness is determined by a re-run of the overall risk assessment to determine if there is any change in vulnerability with the suite of applicable adaptations. The latter are those which are practically implementable and either institutionally compatible or not outside the bounds of realistic institutional reform. Economic efficiency would most likely be incorporated within an assessment against economic objectives. Flexibility is relevant, but is not explicitly considered in the evaluation. Adaptation options would only be selected if they could be 'adapted' to local circumstances.

3.5.3 Barriers to introduction of adaptations

Many of the adaptations described in this section are based on experiences of developed nations with experience of climatic and hydrological variability and with robust institutional arrangements for water resource management. Under current conditions, many of the adaptation options may not satisfy criteria such as cost, implementability and institutional compatibility (Dolan *et al.*, 2001) for World Bank client countries. Successful introduction would require external technical and financial support, as well as institutional strengthening and policy reform. The challenges in establishing an appropriate institutional setting for introducing many of the 'adaptive capacity' options should not be underestimated.

3.5.4 Economic considerations

Groundwater management is fundamental to the sustainability of water resources and there are strong environmental, economic and social reasons that justify government investment in groundwater management and adaptation to climate change. Not least of these is the ability for governments to continue to provide water for basic human needs and groundwater dependent industries such as agriculture.

Across most countries in the world, groundwater is currently supplied for free, or at a minimal fee. Without an income stream, investment by governments in groundwater management is not profitable and is thus often poorly addressed. Successful management and implementation of adaptation options will only occur if there is adequate financial support. Adaptation options must therefore be assessed against economic objectives that factor any initial and ongoing costs, and available means for financing these.

All adaptation options cost money: there is no free or cheap generic solution that will resolve the current and future pressures on groundwater resources globally. But economically feasible options do exist. In developing nations, low-cost low-technology solutions are likely to be more successful. In some cases, the costs and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met.

The economic feasibility of an adaptation option, or suite of options, will depend on a number of factors:

- *Cost of start-up* – costs associated with the initial phases of implementing an adaptation option, for example, building materials and labour to build a managed aquifer recharge scheme, or human resources, software and computer storage for establishing a groundwater database. The cost of start-up will depend on the adaptation type, scale, where materials are sourced from, local access to expertise, the amount of in-kind contributions etc.
- *Ongoing costs* – due to (for example) monitoring and maintenance requirements.
- *Revenue* – whether or not the options have a source of income, such as fees for water usage, to enable some cost recovery.

[7] Benefits not relating to the contribution to avoiding or reducing risks associated with climate change.

- *Local economic conditions* – this will affect costs for materials and labour, and the degree to which a community or country is able to fund the option themselves (versus the need to loan money from elsewhere).
- *External financers* – the availability of financial contributions and/or loans from external sources, and the conditions under which these finances are provided (time frame required for pay back, interest rate levels etc).

The diverse range of managed aquifer recharge (MAR) schemes (see Section 3.4.1) illustrates how the economics of different adaptation options can vary considerably. Low-technology schemes such as surface spreading basins and sand dams are less expensive (about US$10 to US$50 per ML, ignoring pipeline costs) than, for example, borehole injection methods (in the order of US$100 to US$1,000 per ML). Consequently borehole injection methods are often less viable, particularly for agricultural purposes, although in some areas they may be suitable for urban and domestic water use. This provides an example where the economic feasibility is driven not only by cost, but also by other considerations such as the scale of the scheme and the end-user of the water resource.

4. Examples of adaptation measures

4.1 Introduction

Case studies of adaptation in groundwater resource management to climate change and hydrological variability in the United Kingdom, USA and Australia have been prepared. They illustrate approaches to adaptation to climate risks for groundwater dependent systems in contrasting situations, but from countries with relatively mature information bases and institutional arrangements for water resource management. They provide a useful guide to approaches to adaptation to climate change and hydrological variability and also illustrate some of the challenges involved.

The case studies demonstrate a wide range of adaptations across many of the types described in sections 3.1 and 3.2 . The adaptations are primarily in response to water scarcity and to minimize risks to water quality. Measures identified or implemented in the case studies include:

- *Building adaptive capacity* – through understanding the system's exposure and sensitivity to climate risks, conjunctive water resource planning, establishment of markets for water, establishing and applying standards for water use measurement, establishing goals for sustainable levels of water use; increasing end-user engagement in water resource planning and management, separate management of water for consumptive and environmental uses and community education-behaviour change campaigns.
- *Modify exposure to risks from climate change and hydrological variability* – through supply augmentation and diversification, conjunctive planning and use of groundwater and surface water resources, managed aquifer recharge, deepening groundwater utilization bores, protection of source water quality, environmental water provision for groundwater dependent ecosystems and setting and enforcing caps on water use.
- *Modify sensitivity to climate change and hydrological variability* – through improved soil management to increase rainfall infiltration and reduce reliance on irrigation, improve irrigation scheduling and application techniques, urban water demand management (e.g. adjustment of building codes, implementing domestic water conservation measures, water restrictions), adjusting livestock numbers to balance demand for and availability of fodder from irrigated pastures, and land use planning controls to cap local population growth.
- *Avoiding risk* – including through adjustment of agricultural enterprises to reduce requirement for irrigation, balancing grazing livestock numbers to capacity to provide fodder from limited irrigation and sourcing alternative water supplies that are less or not sensitive to climate (e.g. desalination or inter-basin transfer).

4.2 Case study comparison

Steps from the vulnerability assessment framework (described in the larger report) have been used to compare the adaptation case studies and to illustrate commonalities and differences between case study approaches and the vulnerability assessment framework. It is important to note that the methods used in each of the case studies were not based on the vulnerability assessment framework and thus some elements of the framework are not applicable.

4.2.1 Establishing the context

Table 4.1 outlines the context for the four adaptation case studies, based broadly on the first step of the vulnerability assessment framework. Additional contextual information is provided in the case study summaries (Sections 4.3, 4.4 and 4.5).

The water supply systems in each of the case studies are critically dependent on groundwater and all have been exposed to drought/climate change in recent years. Combined with growing demand and/or competition for groundwater from urban and/or rural users, water resource managers in each of the case studies face a declining or potentially declining water supply. In some cases water quality is also under threat. An increasing value on, and legislative requirements to protect, the environment have also influenced the way in which groundwater resources are managed.

Table 4.1 Context for the four adaptation case studies

	Case study			
	UK – East Anglia	**USA – Oro Valley**	**Australia – Gnangara Mound**	**Australia - Hawkesdale**
Location	Eastern England	South west USA	Western Australia	South eastern Australia
Planning timeframe	6-yearly cycle Water allocated on a 12 year timeframe	10-yearly cycle Water allocated on a 100 year timeframe	2030 and beyond	Considers climate change impacts at 2030 and 2070
Ground-water system	Chalk limestone & Crag (gravels, sands, silts & clays) aquifers Groundwater fully allocated. Used for irrigation, residential, commercial & environment Temperate climate	Tertiary sedimentary (sand, gravel, conglome-rate) aquifer Groundwater over-allocated. Sole source for town water supply. Semi-arid climate System is very sensitive to changes in rainfall	Superficial (sand) water table aquifer, plus deeper confined aquifers Groundwater over-allocated. Used for urban water supply, irrigation, industry & the environment. Mediterranean climate Groundwater supports wetland & cave ecosystems	Port Campbell limestone, Newer volcanic basalt, plus deeper confined aquifers Groundwater is used for stock & domestic, dairy and irrigation. Temperate climate Insufficient data to know if the system is fully allocated or not Plantation forestry in the area
Stake-holders	Irrigators, food industry, Environment Agency, residents, Government	Residents, Oro Valley Water Utility, Government	Residents, Government, farmers, tourism and other industries	Irrigators, dairy & forestry industries, stock and domestic users, Government
Key objectives	To meet the future water needs of abstractors without damaging the environment.	To meet future water needs of the Oro Valley township. To balance groundwater use with groundwater recharge	To meet future water demand To protect groundwater dependent ecosystems	To ensure groundwater extraction falls within the 'sustainable yield' of the aquifer+
Success criteria (example)	Meet water quality guideline criteria	Sustainability thresholds for groundwater levels	Thresholds for wetland water levels	NA
Climate change scenarios	Historical, current	Drought conditions	Historical, current	Historical, current, 2030 best/worst case, 2070 best/worst case
Drivers for adaptation	Water use/demand Changes in the value society places on the environment European Water Framework Directive Recent drought	Persistent drought conditions Population growth Declining groundwater levels and reduced well production capacity	Population growth and increased water demand Declining groundwater levels Recent drought Environmental values	Drought State Government policy Increasing demand

+The sustainable yield is the renewable part of the groundwater resource, identified after making allowance for acceptable impacts on users, the surface environment and the resource itself.

With the exception of the Hawkesdale case study, future climate change scenarios are not explicitly included in the water resource planning process. Instead, historical climate and recent drought conditions have been used, assuming that the latter represents a conservative worst-case scenario for the future. There are potential limitations to this approach, as discussed in Section 4.2.6.

4.2.2 Identifying and analysing risk

Table 4.2 summarizes the climate risks identified in each of the case studies and how these risks have been analysed. Across all case studies, the most significant climate hazards are reduced rainfall and increased frequency of drought. Hazards for the groundwater system include reduced recharge, groundwater contamination and an increased demand for water. Each of these is affected by climate, but also by other factors such as land use and population growth.

Pre-existing climate risk controls comprised either (1) further development of the groundwater resource to meet water needs, or (2) limits on groundwater allocation and abstraction to ensure groundwater levels are maintained,

Table 4.2 Case study overview - identifying and analysing risk

	Case study			
	UK – East Anglia	**USA – Oro Valley**	**Australia – Gnangara Mound**	**Australia – Hawkesdale**
Climate hazards	Warmer wetter winters Warmer drier summers Increased frequency of drought and flood	Reduced rainfall Increase in temperature More severe drought	Reduced rainfall Increase in temperature Increased frequency of drought	Reduced rainfall Increased temperature Increased frequency of drought
Climate related hazards for the groundwater system	Delay in the start of the recharge season Shorter recharge season Increased vegetation water use Increased water demand for the public, irrigators and the environment Reduced water quality	Reduced groundwater recharge Increased demand for groundwater	Reduced groundwater recharge Increased demand for groundwater Reduced water supply to groundwater dependent ecosystems	Reduced recharge Increased demand for groundwater, due to a shift from dryland to irrigated agriculture
Pre-existing climate risk controls	Time-limited abstraction licenses Cessation conditions when groundwater or river levels drop below a set threshold.	Further development of groundwater resource	Limits on groundwater allocation Restrictions on groundwater pumping	Further development of groundwater resource
Assess consequences and likelihood of potential climate impacts	Potential consequences are identified (e.g. inadequate water supply for irrigation, domestic use and the environment). However, no formal assessment has been made.	Assessment of sustainable extraction under drought conditions has been made. Future climate change scenarios were not included.	Aware of potential consequences for water supply system and ecosystems. Likelihood of consequences is not documented.	Likelihood of reduced groundwater recharge modeled for each of the climate change scenarios. No assessment of other consequences.
Risk rating	No risk rating	No risk rating	No risk rating	No risk rating

particularly where these sustain important ecosystems or provide a critical potable water supply. In all case studies, it was acknowledged that these measures alone did not form an adequate response to climatic influences and other pressures on the system, particularly in the Oro Valley and Gnangara Mound case studies where declining groundwater level trends occur.

None of the case studies have documented any analysis of climate risk. Whilst water resource managers are aware and are acting upon the consequences of potential climate risks (e.g. inability to meet water needs, decline in ecosystem health, etc.), there is no formal documentation of the likelihood of these consequences occurring.

4.2.3 Evaluating and treating risks

Table 4.3 outlines if and how the case studies have documented processes for evaluating and treating climate risk. The case studies do not document any process for prioritizing climate risks. Uncertainties associated with climate risks are also not addressed, with the exception of the Hawkesdale GMA. In this case probability distributions of rainfall and groundwater recharge were modelled to understand the uncertainties in future rainfall and groundwater recharge (see the larger report for more details).

The case studies have identified a number of adaptation options, across the types previously described in Section 4.1. The assessment of these adaptations has not been documented, but is likely to have included factors such as the ability to meet desired environmental, social and economic outcomes, despite water scarce conditions; ability to meet legislative and regulatory requirements; financial viability; acceptable impacts on local economy and stakeholders, etc.

Case studies have not tested identified adaptations against future climate change scenarios, although they have considered existing climate (including drought) conditions. If future climate change scenarios include conditions worse than the recent drought, this approach could result in under-adaptation. Each of the case studies acknowledge that in the face of future climate change additional adaptations may be required if water resource managers are to meet their key objectives. Additional options raised include: water trading, better conjunctive use of surface water and groundwater, relaxing the development of local groundwater resources and relying more on alternative renewable water resources, and expanding existing approaches such as managed aquifer recharge.

4.2.4 Stakeholder engagement

Stakeholder engagement forms an important component for all of the case studies. The development and engagement of farmer groups in East Anglia provided a powerful tool for educating community and implementing adaptation options. It also created an environment for innovation in water use efficiency, and a communication channel for irrigators to be informed so that they in turn can make sound investment decisions. In the Oro Valley, successful stakeholder engagement is critical for the implementation of their water conservation program.

In the Gnangara Mound, stakeholders are currently being engaged in the development of a sustainability strategy. This strategy is taking a whole of government approach, involving and liaising with diverse groups, including land use planning, water resources, infrastructure, and biodiversity. This provides an opportunity to manage water resources in a holistic way.

In the Hawkesdale GMA, meetings with stakeholders have been used to discuss possible climate change scenarios and impacts, and the likely implications for water allocation and planning. This assists stakeholders to understand what the future may be like and how they as individuals will need to adapt. It also provides an opportunity to address stakeholder concerns, reducing the likelihood of appeals against allocation decisions.

4.2.5 Monitoring and review

Groundwater levels and chemistry are the most common monitoring methods for assessing the impacts of climate and other pressures on the groundwater resource. In the Gnangara Mound and East Anglia case studies, measures for surface water (e.g. levels) and ecological health are also included. This allows conjunctive management of both surface water and groundwater resources.

Table 4.3 Case study overview - evaluating and treating risk

	Case study			
	UK – East Anglia	**USA – Oro Valley**	**Australia – Gnangara Mound**	**Australia - Hawkesdale**
Prioritize risks and assess uncertainty	NA	NA	NA	Uncertainty captured in recharge modeling but no formal prioritization of risk
Identify adaptation options	Changes to abstraction licensing system Development of water abstractor groups Investment in more efficient irrigation technologies Installation of on-farm reservoirs Changes to land management above aquifers	Further groundwater development Water conservation Enhanced aquifer recharge Import surface water Reclaimed water use	Supplemental water for wetlands Re-hydrate cave systems Limit groundwater abstraction Alternate water sources (wastewater, desalinated sea water) Enhance recharge via MAR and land use change Demand management Sustainability strategy	Further development of groundwater resources, including deeper confined aquifers Groundwater use not currently included in policy (e.g. plantations) to be incorporated. Groundwater allocation limits Manage land use and its impacts on recharge
Assess adaptation options	Not documented	Not documented	Not documented	Not documented
Plan and implement adaptation options	Options have been implemented	Some options have been implemented	Some options have been implemented or started to be implemented	With exception of allocation limits, options have not been implemented

Currently there is very limited monitoring of groundwater in the Hawkesdale Groundwater Management Area, and this inhibits the understanding of the resource and the impacts of any change. Modelling approaches have been used to better understand the likely impacts here and monitoring bores have been recommended so real changes can be observed in the future. In the Oro Valley, groundwater is the only source of potable water supply and consequently levels are closely monitored to ensure security and reliability of supply.

In each of the case studies, water resource managers undertake periodic reviews of available data, including measurements of both the groundwater system (e.g. levels) and external pressures on the system (e.g. climate, population growth, metered groundwater use). Review of these data may be used to better understand the system and to assess the success of current and/or need for further adaptation. Where existing monitoring data cannot be used to measure established success criteria, additional monitoring may needed.

4.2.6 Observed success factors and barriers for adaptation

The case studies provide useful insights to both the success factors and barriers for implementation of adaptation options. Success factors identified include:

- *A multi-faceted approach* – ensures that outcomes are not reliant on a single or small group of measures. Incorporating ways to both enhance supply and reduce demand is more effective than looking at either of these approaches in isolation. Capacity building is also a vital component of any multi-faceted approach.

- *Collective action* – to be most effective, adaptation measures need to be supported at a range of levels (e.g. local, region, state) and across different groups (government, community, industry, etc). This ensures that decisions are based on a broad knowledge base and that the adaptation approach is consistent with everyone working towards common objectives. Collective action also provides a means for sharing risk.
- *Strong hierarchy of values* – clear objectives and a strong values hierarchy are required to determine an appropriate response for restricting or supplementing resources that are put under pressure by climate change.
- *Adaptations with multiple benefits* – provides additional justification for investment and encourage stakeholder buy-in.
- *Adequate capacity* – the availability of appropriate skills, knowledge and time is required to make sound decisions and to implement adaptation options. It is also important that local capacity is available (either currently or through training and development) for the ongoing implementation and maintenance of any adaptation option.

Barriers for successful adaptation comprise factors that prevent adoption, or that result in adaptation decision errors. Factors preventing adoption include:

- *Costs* – inability to justify the level of investment required to implement adaptation, due to lack of confidence in the benefits of adaptation or inadequate supply of funds.
- *Behaviours and attitudes* – community expectation regarding the quantity of water that will be available for their use in the future is a significant driver for water demand and a barrier for successful implementation of water conservation measures. It is difficult for people to change their perceptions and behaviours, and to accept that things in the future will be different to the past. Effective stakeholder engagement is able to mitigate some of these problems.
- *Uncertainty* – there are a number of uncertainties that impede investment in adaptation options, particularly large capital investments that require confidence in the future availability of water, future demand, and the economic environment. It is therefore important to incorporate uncertainty into the decision making process.

Factors that may contribute to adaptation decision errors are:

- *Lack of knowledge* – poor understanding of the significant drivers for current and future change in a groundwater system, including climate change, population growth, cultural, political and economic contexts etc. can lead to misinformed decisions. The first step to identify adaptation options should be to establish the context including identification of all the significant drivers.
- *Inadequate scenario planning for the future* – in three of the four case studies, projected climate change was not explicitly considered in the development of adaptation options. Instead the focus was on meeting water demand under recent drought conditions and using this as a 'worst case' basis for the future. This approach is fine, as long as these claims are founded by comparing recent drought conditions to future climate change projections. However, the Hawkesdale study illustrates that in some cases such an approach may be inadequate and that rainfall and recharge under worst case climate change scenarios may be much less than under the drought conditions of recent years. If the worst case climate change scenario is realized, basing decisions on historical drought data may lead to under-adaptation.
- *Conflict of interest* – short-term versus long-term interests, potential conflict of interest by decision makers.
- *Inadequate evaluation of adaptation options* – against economic, social and environmental criteria. Evaluation based only on current conditions, not the projected future environment.

None of the case studies have used an established framework for assessing vulnerability. In particular the case studies are lacking in a formal assessment and prioritization of risk. Whilst adaptations may be developed without a vulnerability assessment framework, there are significant benefits in doing so:

- It ensures that critical steps are incorporated into the decision making process.
- It allows users to analyse the elements of risk and to document the assumptions and priorities behind the risk assessment

- A sound understanding and documentation of the issues, objectives and likely risks helps to justify investment for adaptation.
- Prompts users to evaluate adaptation options against established criteria and objectives, to see if the desired outcomes will be met and if it is worthy of investment.

4.3 UK case study summary

Background

The United Kingdom case study (see larger report for full case study) considers the management of groundwater in East Anglia, in eastern England. East Anglia is the most intensively cultivated arable region in the UK. Groundwater is widely used for supplemental irrigation, as well as for residential and commercial purposes. While use for irrigation has been relatively stable, demand from other uses has been growing. With projected climate change, demand for irrigation is expected to increase and supply to decrease, exacerbating pressures on resources.

Groundwater management arrangements

Groundwater is managed under the same general arrangements as surface water in the UK. Groundwater use has been managed in England for many decades. An abstraction license, issued by the Environment Agency, is required for uses exceeding 20 m^3/d. Historically, abstraction licenses were generally not time-limited, but all new licenses are time-limited normally to 12 years, although with a presumption of renewal (i.e. priority over new applicants provided water is available). Most abstraction licenses have cessation conditions attached which require abstraction to stop immediately if groundwater or river levels drop below a set threshold. Licenses are issued on a first-come first-served basis without prioritizing uses, but during droughts, priority for groundwater use is given to maintaining public water supply, then environment and finally irrigation.

Groundwater resources and climate change

Much of East Anglia is underlain by productive aquifers, in particular by the Cretaceous Chalk and younger Pliocene-Pleistocene Crag. Both are generally water-table aquifers, although the overlying superficial deposits exert strong controls on groundwater flow and groundwater age. The Chalk is the most important aquifer within Great Britain.
Groundwater is used for domestic, industrial and commercial water supply, irrigation, environmental allocations and to support recreation. About 37% of water use is from groundwater. Across UK, only about 150 000 ha of agricultural land is irrigated, with usage accounting for about 160 000 ML of water in a 'dry' year. The licensed volume of groundwater abstraction for irrigation has declined in the east of England in recent years, although actual use has been stable for many years. Despite its small volumetric demand, irrigation is of significant economic importance to farmers, growers, and the food industry, improving crop yields, quality, consistency and reliability. Competition for groundwater is likely to increase in future, reflecting reduced supply due to projected climate change and growing demand from other sectors, including domestic use and environmental water provision.

Long-standing groundwater management legislation has meant that groundwater uses in East Anglia have been controlled. As a consequence there are no consistent long-term trends in groundwater resource status. Groundwater levels are generally controlled by the regional recharge and rise and fall in line with variations in rainfall. Although groundwater resources are stable, assessments have indicated that there is little groundwater available for further abstraction in many groundwater units.

Climate change is projected to have several direct impacts on groundwater in East Anglia. Drier summers and increased summer and autumn potential evapotranspiration are projected to delay the wetting up of soils and postpone commencement of the recharge season. With warming conditions, potential evapotranspiration is projected to be greater in spring, leading to more rapid drying of soils and a shortening of the recharge season. Reduced recharge in response to these factors may be at least partly offset by projected wetter conditions during winter, although recent work suggests there will be an overall reduction in groundwater recharge. Warmer and drier conditions during summer are likely to increase demand from all of the current uses. The need to reduce climate-induced stresses on vulnerable aquatic or groundwater-dependent terrestrial ecosystems could further reduce the availability of groundwater for use in irrigated agriculture.

Adaptation to climate change and hydrological variability

The water environment in the UK is heavily controlled, with the European Water Framework Directive the dominant influence. Its objective of achieving Good Ecological Status in all surface water bodies (and Good Status in groundwater bodies) by 2015 and beyond, and short-term economic pressures faced by agriculture, mean that few irrigators in eastern England are deliberately or specifically adapting to projected climate change. They and the abstraction licensing authority are adapting to water scarcity though in ways that should help them cope with the projected impacts of climate change. Adaptations include:

- Changes to the abstraction licensing system that enable adaptive management - a 6-yearly water resource planning cycle has been introduced to help ensure sustainable levels of abstraction are maintained in the face of changing supply conditions. Management arrangements ensure that abstraction decisions take place at a local level and that surface water and groundwater resources are managed conjunctively in each water management unit. License trading within management units is now permitted to encourage better utilization of scarce resources.
- Development of Water Abstractor Groups – the formation of such groups has empowered farmers to influence water policy and participate in resource management decision-making.
- Investment in more efficient irrigation technologies and better irrigation scheduling to reduce demand for water.
- Installation of on-farm reservoirs to capture and store surface flows in winter and provide alternative supplies to groundwater to help meet summer demand.
- Changes to land management to reduce water quality threats to groundwater resources from excessive use and leaching of nitrogenous fertilizers.

Discussion

While climate change is not a significant driver, a range of potential adaptations to water scarcity have been implemented in East Anglia. By helping to build the adaptive capacity of the irrigation sector and helping to reduce demand, they are developing resilience to observed climate variability and projected climate change.
Despite successes in implementation of adaptations, significant barriers or limitations exist. The short duration of abstraction licenses means that confidence among irrigators may be insufficient for the major capital investments to increase resilience. The combination of short-term economic uncertainties surrounding agricultural production, limited financial support from Regional Development Agencies and uncertainty over water availability also are barriers.

The sharing of water resources through water trading has yet to develop in the UK, even though legislation allows it. This reflects in part uncertainty over the processes involved and the greater simplicity of existing informal practices of renting or purchasing land with abstraction licenses that are used by farmers. The potential for water trading is large, as many abstraction licenses are never used and more are only partially used. Trading would allow water to be used where most needed. The danger however is that in areas where water resources are already under pressure, the re-activation of sleeper or unused license could cause an even greater conflict between the environment on the one side and the abstractors on the other.

Whilst the adaptation measures that have been discussed have increased the efficiency of utilization of groundwater, they have not fully exploited the abstraction opportunities afforded by better conjunctive use of surface and groundwater. It is suggested that adapting conjunctive use guidelines to make more use of the higher river flows in the “wetter” winters and saving groundwater for when rivers are low; and/or making better use of the difference in timing between high irrigation demand and low groundwater levels might further increase resilience.

The adaptation options already implemented are unlikely to be sufficient to cope with the range of future water resource outcomes anticipated by climate and socio-economic change. Given the likely increasing future demand for a diminishing resource, it is likely that further adaptation will be required, which might include further restriction of irrigation to the highest-value crops or a move to non-irrigated agriculture or livestock.

4.4 USA case study summary

Background

The case study (see larger report for full case study) considers improved management of groundwater supply to meet the future needs of residents of the township of Oro Valley (the Town) in the semi-arid south-west of the USA. Challenges associated with persistent drought conditions, which may be attributed to global climate change, are being incorporated into long-term water resource management planning by the Town.

Recent climate changes have resulted in decreased precipitation and surface runoff causing a significant drop in recharge to groundwater throughout south-western USA. Local groundwater resources have historically been the principal source of potable water supplies of the Town. Population growth is placing increasing demands on the groundwater supply. Ten years of persistent drought and the accompanying reduction in recharge to groundwater have caused water levels in the sole source aquifer to decline significantly. The drop in water levels and a reduction in well production capacity in some wells caused the Town to investigate groundwater availability and develop altered approaches to groundwater management.

Groundwater management arrangements

A water right is required in the State of Arizona to withdraw surface water or groundwater. Groundwater rights within the U.S. are managed individually by each of the fifty states. In Arizona, water rights are based on the doctrine of prior appropriation, which simply stated is a right of "first in time, first in right". A water right is generally required for industrial, irrigation, and municipal needs. Most domestic uses are exempt from obtaining a water right.

The transition from agricultural to urban population base is occurring in the region's major metropolitan areas, Tucson and Phoenix. This transition would not have been possible without allowing the transfer of water rights from agricultural (irrigation) to potable use. Many of the water rights for agriculture are very senior rights and typically the water rights are sold with the land. In these major metropolitan areas, groundwater is fully appropriated. So development is dependent on having the right to use the water.

In 1980, the State of Arizona adopted a *Groundwater Management Act* that includes the Assured Water Supply (AWS) program. The AWS program requires water service providers, including municipalities and developments located in unincorporated portions of the counties, to demonstrate that an AWS will be physically, legally, and continuously available for the next 100 years before the developer can record plats or sell parcels of land. The provider must prove that a 100-year groundwater supply is available by either satisfying the requirements to obtain a Certificate of Assured Water Supply or by a written commitment of a water service provider with a Designation of Assured Water Supply. Managed by the Arizona Department of Water Resources (ADWR), this program has created a process that requires a study be completed to ensure that a long-term supply exists, that each successive AWS designation does not adversely impact pre-existing rights, and that recharge to the aquifer is considered (although potential impacts of climate change are not considered).

Groundwater resources and climate change

The Town of Oro Valley is located within the Basin and Range geographic province, which generally consists of north to south trending basins separated by north to south trending mountain ranges. The basin is about 8 km in width in the Oro Valley area, but extends to about 29 km north to the Falcon Valley area. The stream channel consists of basin-fill deposits, comprising granular sands and gravels that are highly permeable, readily accept streamflow infiltration, and therefore are optimum as a catchment area for recharge.

Recharge to the aquifer system in the area occurs from infiltration along adjacent mountain fronts, underflow from north-eastern parts of the Oro Valley area, and stream channel recharge along ephemeral drainage lines. Based on estimated recharge rates, average rates of groundwater recharge at the mountain fronts and stream channels in the Oro Valley vicinity are estimated at about 4.7 to 9.6 GL/y. Based on this range, average annual local groundwater recharge totals about 7.2 GL. The quantity of annual groundwater recharge is consequently reduced by the affects of drought.

Results of the study imply that there is an exponential rather than linear relationship between recharge and precipitation. As a result, mountain front recharge is believed to be sensitive to a relatively small reduction in precipitation. After 1995, when the average annual precipitation rate decreased to about 25 cm/y, it is anticipated that a significant reduction in recharge occurs. It is conjectured that stream channel recharge is similarly reduced as well. Actual reduction of natural groundwater recharge under persistent drought conditions remains unclear based on available data, but is considered to be significant.

Adaptation to climate change and hydrological variability
Adapting to uncertain changes in supply caused by multiple pressures, including climate change, has become a high priority. The impacts to groundwater caused by climate changes include declining water levels or other stresses that are not easily predictable and uncertain.

The use of groundwater by the Town is controlled by water rights (groundwater is fully appropriated) and groundwater regulations that affect Oro Valley and other water providers in the region that tap the same aquifer. Groundwater pumping has increased in the last 10 years at a faster rate than is being recharged, and groundwater levels are dropping. Model predictions indicate increased pumping will not sustain groundwater availability. Therefore the Town has developed, and is beginning to implement, multiple strategies that include water conservation, use of reclaimed water in lieu of potable water, improved storm water capture to enhance groundwater recharge, better engineered wells to improve capture and manage groundwater in a sustainable manner, shift water between sectors (agriculture to urban), and import surface water sources to supplement and reduce demand on groundwater.

The Town has taken significant steps to secure new water supply sources to alleviate the effects of over-drafting the groundwater aquifer system and impacts due to climate change. Current and future water resource planning and management adaptations include:

- groundwater development based on sustainability criteria;
- augment water supplies by importing reclaimed water and treated central Arizona project water;
- implementation of water conservation policies;
- enhance local groundwater recharge, including through improved storm water management.

All of these options consider technical, financial, legal, political, institutional, and environmental impacts. The Town is adopting impact fees to finance and implement current and future strategies.

4.5 Australian case study summaries

Two contrasting groundwater management case studies have been documented for Australia, the first relating to the Gnangara Mound in Western Australia and the second to the Hawkesdale Groundwater Management Area (GMA) in south-western Victoria. The Gnangara Mound is an important groundwater resource for the city of Perth, however it also supports groundwater dependent ecosystems with very high conservation value. The Hawkesdale GMA is in a largely rural region, with groundwater primarily used for irrigation and on-farm domestic and livestock use.

The case studies also illustrate differences in groundwater management arrangements between jurisdictions. Under Australia's constitution, groundwater management is the responsibility of State or Territory governments. This means that whilst there is general agreement between the different jurisdictions, individual governments have somewhat differing approaches to water allocation and planning. Consistent features of the approach include state ownership of water, with allocation of rights to access and use water being controlled by government. Allocation policies vary in detail but are all aligned on an approach to the sustainable allocation of groundwater in keeping with the concept of safe yield. Generally groundwater allocation for consumptive use will only be permitted where the resource can be maintained sustainably over the long term. Individual jurisdictions differ in the definitions of sustainability and in the legislative mechanisms that are available to manage allocation.

4.5.1 Management of the Gnangara Mound, Western Australia

<u>Background</u>
The Gnangara Mound case study considers the situation of a large shallow aquifer which has many ecological, social and economic demands. This aquifer and associated groundwater dependent ecosystems are highly sensitive to relatively small changes in storage volume. Management of water level is the key issue, given the range of interactions with the surface of the aquifer.

The Gnangara Mound is an area of sandy aquifer material that is open to direct groundwater recharge, located around and to the North of the city of Perth, Western Australia. It covers an area of approximately 2,200 km^2. The aquifer is underlain by shallow exposed sands and is largely dependent on rainfall recharge for water supply.

<u>Groundwater management arrangements</u>
The Department of Water is the manager of the State's water resources. It has the responsibility for planning and managing groundwater use on the Gnangara Mound for the benefit of the community. This involves identifying and protecting important groundwater dependent ecosystems and managing private and public water supply abstraction to protect those systems. The Department regulates the Water Corporation (the water retailer) and private use through licensing and monitors impacts on water levels and ecosystems.`

Western Australia's Integrated Water Supply System (IWSS) is the key integrated system which provides potable water for Perth and surrounding areas. This system relies heavily on water pumped from the Gnangara system. Approximately 45% of groundwater pumped from the Gnangara system is for the IWSS. Current management criteria also set out private groundwater allocation quotas of 60.6 GL/y from the Gnangara Mound.

<u>Groundwater resources and climate change</u>
The Gnangara Mound is a term used to describe an interconnected groundwater system that consists of three partially connected aquifers, the superficial (water-table) aquifer (the Gnangara Mound proper), the Leederville aquifer and the Yarragadee aquifer. The latter two are deeper and generally confined aquifers that extend north and south of the superficial aquifer extent. The aquifers of the Gnangara system represent one of the largest sources of potable water in south-western Australia.

While abstraction of groundwater occurs across the system, impacts of abstraction predominantly manifest on the mound, that is, upon the shallow aquifer units. It is these shallow units that are most affected by changes in rainfall and hence by climate variability and change. The aquifer system is finely balanced and the response to changes in climate is likely to be felt in the short rather than long term, impacting for example a number of groundwater dependent wetlands that are already affected by recent dry weather.

Groundwater levels within the Gnangara Mound have been trending downwards for the last 30 years. The centre of the decline is largely within the central mound region where drawdown up to 6 m has occurred over this period. Typically drawdown is in the range of 1 to 2 m. This coincides with a general trend of declining annual rainfall across the south west of Western Australia. Abstraction and land use impacts on recharge are also implicated in declining groundwater levels. Climate change projections for the region are for further reductions in rainfall, with likely consequent impacts on recharge.

<u>Adaptation to climate change and hydrological variability</u>
Several measures have been introduced or are consideration to enable the Gnangara system to adapt to experienced climate change. Measures are directed at protecting important groundwater dependent ecosystems and maintaining supplies for consumptive uses. Adaptations identified include:

- Wetland supplementation – in which water is harvested from other locations and used to maintain wetland levels and ecological values. Two wetlands are currently supplemented on the Gnangara Mound, using water pumped from the shallow superficial and deeper Leederville aquifers.

- Cave system rehydration – during summer (when groundwater levels are lowest) re-hydration of a limestone caves system has been achieved by pumping water from a lake or from groundwater bores and using this to enhance recharge in the vicinity of caves. The increased recharge re-hydrates the caves and, by maintaining the end-of-summer levels, ecosystem function is supported.
- Limiting groundwater abstraction – licensed pumping is tightly controlled to limit the inter-annual fluctuation or the overall decline in the vicinity of wetlands. In some areas, superficial bores have been switched off in an effort to meet wetland water level criteria.
- Assessing managed aquifer recharge for the area – one project has trialed injection of reclaimed water (i.e. treated municipal effluent) into the deeper (Leederville) aquifer as a pilot to prove the feasibility of future injections. A trial is also planned for the superficial aquifer.
- Exploring alternative land uses after existing pine plantations are harvested – land use may be changed to enhance rainfall recharge in key areas that are currently in recharge deficit.
- Establishing a horticultural precinct using treated wastewater rather than potentially potable water from the Gnangara Mound.
- Changing land management (e.g. burning of *Banksia* woodlands) to increase recharge and maintain biodiversity values.
- Revising groundwater allocation to public and private water supplies.
- Development of the *Gnangara Sustainability Strategy (GSS)*[8], a whole of government approach to ensure the sustainable use of water for drinking and commercial purposes and to protect the environment. This strategy considers both water and land use impacts on the groundwater resource.

The major constraint on adaptation to changed climate conditions in the Gnangara Mound is the expectation of communities that water will always be available in the same quantities for consumptive use. In some cases lower water use activities are considered but in most of the examples, alternate sources of water are used to substitute for existing groundwater. This brings with it increased costs and lowered certainty of supply. In some cases lower quality water may need to be used.

As parts of Perth's metropolitan supply is now from desalinated sea water, there is an element of substitution of groundwater for "manufactured" water. This is an example where the ecological value of wetlands that were groundwater fed is considered high enough to ensure that they are supplied by any available water.

4.5.2 Hawkesdale Groundwater Management Area, Victoria

<u>Background</u>
The Hawkesdale case study is also for a large volume aquifer system, but one in which recharge and use are currently considered to be approximately in balance. However this system may move out of balance due to climate change and would also do so if growing demand for groundwater for irrigated agriculture were to be satisfied.
Groundwater extraction is widespread across the Hawkesdale GMA. Approximately 2,300 bores are registered as possible extraction bores. Most are registered for stock and domestic use, with some used in dairies and for irrigation of pastures and fodder crops.

<u>Groundwater management arrangements</u>
The Victorian Government, through its water policy statement, *Our Water Our Future*, has made the commitment of bringing all the state's water resources under a sustainable water allocation regime. For groundwater, this means ensuring that all extraction falls within limits defined by the 'sustainable yield' of the aquifer. The sustainable yield is the renewable part of the groundwater resource, identified after making allowance for acceptable impacts on users, the surface environment and the resource itself.

<u>Groundwater resources and climate change</u>

[8] http://portal.water.wa.gov.au/portal/page/portal/gss

The Hawkesdale GMA covers an area of approximately 1400 km^2. The Newer Volcanic Basalt (NVB), Port Campbell Limestone (PCL), Clifton Formation and Dilwyn Formation form the significant aquifers in the Hawkesdale GMA. Over much of the Hawkesdale GMA, the Narrawaturk Marl and Gellibrand Marl are considered aquitards that are believed to effectively hydraulically separate the Clifton Formation Aquifer from the underlying Dilwyn Formation Aquifer and the overlying PCL Aquifer respectively.

There is no groundwater monitoring of the key Port Campbell Limestone aquifer within the Hawkesdale GMA. Anecdotal evidence is provided by local groundwater users that suggests groundwater has been declining significantly for the past five years or so. This is consistent with a prolonged spell of relative dry conditions, which may reflect early signs of human-induced climate change.

Worst case climate change projections for the Hawkesdale GMA are for significantly less rainfall and recharge than has been experienced in the most recent (relatively dry) 10 year period. Temperatures are also projected to increase. Groundwater recharge is projected to decline by an even larger amount.

Adaptation to climate change and hydrological variability

Low rainfall over the past decade has resulted in several adaptive responses already being implemented by local groundwater users. These have primarily taken the form of changes in agricultural enterprise, although more direct measures have also been developed. Adaptations have included:

- Reducing the stocking rates and herd sizes for given properties to match the available feed (that can be produced without irrigation) to the grazing pressure.
- Introduce irrigation of fodder crops or pastures into the enterprise to reduce reliance on rainfall. As this is likely to put considerable pressure on groundwater resources this approach has not be favoured by the water managers to date.
- Restrictions on the volume of licensed groundwater allocations offered to the public, through the relevant government agency reducing the availability of water licenses.
- Re-drilling and deepening bores which dry up as a result of reduced water levels.
- Targeting deeper aquifers which are confined and not as affected by direct recharge reduction.

Key barriers to adaptation are around the ability to develop profitable farm enterprises that can operate in a reduced rain environment, or at best a reduced security of rainfall. The key adaptive changes for this area are in policy responses to water allocation, including:

- groundwater allocation limits – new (lower) limits will need to be set in light of the likely reduction in available recharge. As with the Gnangara Mound case study, this area is likely to see reductions in recharge resulting from climate change;
- incorporation of uses of groundwater that have not so far been incorporated – in this area there is a potential for significant water use by plants, especially from forestry plantations that have been established in parts of the GMA over the last decade. Currently the relevant State government department is considering policy responses to water use by plantations.
- acknowledging the role of land use – land use dictates the pattern of recharge for the Hawkesdale area. Changes in land use, such as forestry plantations and/or cropping and/or irrigation will significantly change the recharge pattern. This in turn will have implications for recharge and hence the available resources.

5. Conclusions

Compared to surface water, groundwater is much more compatible with a highly variable and changing climate. Aquifers have the capacity to store large volumes of water and are naturally buffered against seasonal changes in temperature and rainfall. They provide a significant opportunity to store excess water during high rainfall periods, to reduce evaporative losses and to protect water quality.

Groundwater is a critical component of adapting to hydrologic variability and climate change. Groundwater options for enhancing the reliability of water supply for domestic, industrial, livestock watering and irrigation include (but are not exclusive to):

- *Integrating the management of surface water and groundwater resources* – including conjunctive use of both groundwater and surface water to meet water demand. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle.
- *Managing aquifer recharge (MAR)* – including building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. MAR is among the most promising adaptation opportunities for developing countries. It has several potential benefits, including storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.
- *Land use change* – changing land use may provide an opportunity to reduce groundwater losses from evapotranspiration, to enhance recharge, and to improve groundwater quality. Changes in land use should not result in adverse impacts to other parts of the environment.

Groundwater is also vulnerable to climate change and hydrological variability. Potential climate risks for groundwater include reduced groundwater recharge, sea water intrusion to coastal aquifers, contraction of freshwater lenses on small islands, and increased demand. Groundwater can also be affected by non-climatic drivers, such as population growth, food demand and land use change. Active consideration of both climatic and non-climatic risks in groundwater management is vital.

Effective, long-term adaptation to climate change and hydrologic variability requires measures which protect or enhance groundwater recharge <u>and</u> manage water demand. Adaptation to climate change can't be separated from actions to improve management and governance of water reserves (e.g. education and training, information resources, research and development, governance and institutions).

Adaptation needs to be informed by an understanding of the local context, and of the dominant drivers (and their projected impact) on groundwater resources in the future. Adaptations must be carefully assessed to ensure that investment in responses to climate change and hydrological variability is proportional to risk and that these responses do not inappropriately conflict with other social, economic, resource management or environmental objectives. Adaptations should not add further pressures on the global climate system by significantly increasing greenhouse gas emissions.

Adaptation options need to be economically viable. In some cases the cost and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met. An economic assessment of adaptation options should factor any initial and ongoing costs, and means for financing these. It must also take into account the local economic environment, which can vary significantly between and within nations.

In many cases, adaptations to reduce the vulnerability of groundwater dependent systems to climatic pressures are the same as those required to address non-climatic pressures, such as over-allocation or overuse of groundwater. Such 'no regrets' adaptations can be implemented immediately in areas where water resources are already stressed, regardless of concerns about the uncertainty of climate change projections and assessments of impact on groundwater and surface water resources.

Successful examples of groundwater adaptation to climate change and hydrologic variability exist in both developed and developing nations. A list of available adaptation options is included in Section 3 of this report. Summaries of adaptation case studies from three developed nations (England, America and Australia) are provided in Section 4.

6. Recommendations

To improve the capacity for and uptake of groundwater adaptation, the following recommendations are made:

1. **Support adaptation case studies from developing nations** – adaptation case studies from three developed nations were reviewed in the current report. As part of the global groundwater governance project, a series of in-depth case studies and evaluations should be prepared for developing countries. Possible case study countries could include: Brazil, China, India, Kenya, Mexico, Morocco, Philippines, South Africa, Tanzania and Yemen. Transboundary aquifers might also be considered, potentially including:
   - the Nubian sandstone aquifer system – this aquifer is located in north-eastern Africa and spans the political boundaries of four countries: Chad, Egypt, Libya and Sudan;
   - aquifers that span across the fourteen countries in the South African Development Community (SADC)

   These case studies would provide guidance to water resource managers in similar settings on improving groundwater governance and conceptualizing and implementing adaptation programs. As a minimum the case studies should focus on examples of MAR, improved management of groundwater storages, conjunctive planning and management of groundwater and surface water and reform of water governance.
   The case studies should cover a range of biophysical and institutional settings and be representative of different kinds of experienced climate change or climate risk impact.

2. **Promote groundwater management and development opportunities** – identify and integrate opportunities to manage and develop groundwater in future water sector programs to improve the reliability of water supply. This may include supporting:
   - Assessments of climate vulnerability.
   - Assessment of the suitability of MAR – to determine the potential viability for MAR. This assessment should identify areas of current water stress (i.e. need), water availability (e.g. excess wet season surface flows, treated waste water), potential storage, and the likelihood that groundwater quality will be suitable for the required use or uses.
     If MAR is deemed viable, subsequent tasks should include:
     - Identification and prioritization of water-stressed areas, particularly focusing on areas of current or foreseeable shortages in drinking water supply.
     - Mapping of MAR potential within the identified priority areas. If possible, this should be undertaken at a 1:100,000 to 1:250,000 scale. This will help prioritize areas for site specific investigation and demonstration projects. Suggested criteria for mapping MAR potential are summarized in Section 3.4.1.
     - Identification of institutions that may take responsibility for regulation, licensing and monitoring of MAR schemes
     - Identification of potentially suitable types of MAR, mindful that in developing countries the most successful, low-risk MAR schemes are likely to be of simple technology and low cost. Examples of different MAR schemes are provided in Section 3.4.1.

     Any planning for MAR should be coupled with demand management strategies.
   - Capacity building in groundwater management and planning. This may include activities such as groundwater resource assessments to better understand the resource, establishing and populating groundwater databases, increasing the level of hydrogeological expertise by establishing or improving accessibility to groundwater training institutions, a manual for groundwater management to outline minimum good practice standards, etc.
   - More integrated management of water resources. This may include conjunctive water use and assessing the impacts of existing or proposed infrastructure to identify any potential inefficiencies or adverse impacts that may be treated to achieve optimal use of water resources.

3. **Disseminate knowledge** - Information from this report and developing country case studies should be disseminated to World Bank staff as part of the overall sector analysis on Climate Change and Water.

4. **Collaborate with programs and partner agencies with specialized knowledge** – including:

- Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) – the GRAPHIC project is hosted by IHP UNESCO, IGRAC and GWSP and focuses on understanding the impacts of climate change and other pressures for groundwater, globally;
- International Association of Hydrogeologists (IAH), and
- International Groundwater Resources Assessment Centre (IGRAC)

7. Glossary of terms

(Source: Bates *et al.*, 2008, except where noted)

Adaptation
Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

Adaptive capacity
The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.

Aquifer
A rock formation, group of rock formations, or part of a rock formation that combines sufficient permeable material to yield economic quantities of water to wells and springs.

Climate
Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change
Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Climate model
A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterisations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions.

Climate projection
A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the

emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

Climate scenario
A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Confidence
As defined by the IPCC, the degree of confidence in being correct is described as follows:

Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

Coping range
The range within which a system has the capacity to cope with some level of variability (in this case to climate or hydrology) without impairment.

Detection and attribution
Climate varies continually on all time scales. ***Detection*** of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. ***Attribution*** of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Downscaling
Downscaling is a method that derives local-to regional-scale (10 to 100km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Emissions scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) new emission scenarios, the so-called SRES scenarios, were published.

Ensemble
A group of parallel and model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty than is possible with traditional multi-model ensembles.

Exposure
In the context of this report, exposure refers to groundwater dependent systems being subjected to adverse effects of climate change and hydrologic variability.

Evapotranspiration
Loss of water to the atmosphere via direct evaporation or transpiration by vegetation.

Flexibility
The flexibility of a system refers to its ability to adapt to a wide range of operating conditions through relatively modest and inexpensive levels of redesign, refitting or reoperation (Hashimoto, T. *et al*., 1982a).

General Circulation Model
See *Climate model*.

Greenhouse effect
Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth’s surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth’s surface. Thus greenhouse gases trap heat within the surface troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming solar radiation, whereas the Earth’s surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

Greenhouse gas (GHG)
Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth’s atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal

Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Groundwater
The water contained in interconnected pores, gaps or fractures located below the water table in an unconfined aquifer, or in a confined aquifer.

Groundwater dependent systems
Those systems that rely on groundwater for survival, including human populations, industries (e.g. agriculture) and ecosystems.

Groundwater development
The abstraction of groundwater for human use.

Groundwater discharge
The process by which water is lost from groundwater, including evapotranspiration, flow to streams, springs, wetlands and oceans, and pumping from wells.

Groundwater management
The management of groundwater resources to meet established objectives for the water resource. Example objectives include: ensuring availability of the groundwater resource into the future, meeting environmental water requirements, meeting water quality criteria to be able to provide potable water supply, etc.

Groundwater recharge
The process by which water from the surface enters the groundwater system.

Hydrological cycle
The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again (AMS, 2000). The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

(Climate change) Impacts
The effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:
– *Potential impacts*: all impacts that may occur given a projected change in climate, without considering adaptation.
– *Residual impacts*: the impacts of climate change that would occur after adaptation.

Likelihood
As defined by the IPCC, the likelihood of the occurrence/outcome is described below:

Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

Managed aquifer recharge
Involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge.

Mitigation
Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to Climate Change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.

No-regrets policy
A policy that would generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs.

Palaeoclimate
Climate for periods prior to the development of measuring instruments, for which only proxy climate records (such as may be determined from tree rings, geology, or ice cores) are available.

Projection
A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

Reliability
Reliability is defined as the likelihood that services are delivered (no failure) within a given period, expressed as a probability. High probabilities indicate high reliability (Hashimoto, T. *et al.*, 1982b).

Resilience
A. The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

B. Resiliency is the speed at which the system recovers from a failure, on average. Shorter recovery periods indicate higher resiliency (Hashimoto, T. *et al.*, 1982b).

Risk
The potential for realization of unwanted, adverse consequences; usually based on the expected result of the conditional probability of the occurrence of the event multiplied by the consequence of the event, given that it has occurred. What makes a situation risky rather than uncertain is the availability of objective estimates of the probability distribution. (USACE, 1992)

Robustness
In a water resources system, robustness refers to the extent to which a system design is able to deliver optimal or near-optimal levels of service over a range of demand (input) and supply (resource) conditions (Hashimoto, T. *et al*., 1982a).

Scenario
A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Sensitivity
Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Stationarity
Stationarity assumes that natural systems fluctuate within an unchanging envelope of variability. Stationarity is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains (Milly *et al.*, 2008).

Threshold
The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Uncertainty
A. An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

B. Uncertain situations are those in which the probability of potential outcomes and their results cannot be described by objectively known probability distributions, or the outcomes themselves, or the results of those outcomes are indeterminate (USACE, 1992)

United Nations Framework Convention on Climate Change (UNFCCC)
The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD member countries in the year 1990 and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994.

Vulnerability
A. Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

B. Vulnerability refers to the severity of the likely or expected consequences of failure (Hashimoto, T. *et al.*, 1982b).

Water table
The surface between the unsaturated and saturated zones of the subsurface at which the hydrostatic pressure is equal to that of the atmosphere.

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