Pathways for realizing water conservancy in irrigation systems

Shahbaz Khan[1]

1. Introduction

As elsewhere in the world, Australia's irrigation systems suffer from problems associated with losses in storage and conveyance, on-farm losses and variable water use efficiency. In the Murray–Darling Basin (MDB) it is widely accepted that 25 percent of diversions for irrigation is lost during conveyance in rivers, 15 percent is lost from canals and 24 percent is lost on farm, meaning that only 36 percent of irrigation water is actually delivered to plants. Such losses are not atypical across the world (Table 1). The data in Table 1 for the Murrumbidgee Irrigation Area (MIA) do not include river conveyance losses and indicate on-farm losses better than the overall MDB average (Khan *et al.* 2004). However, given that the world will need to feed 1.5 to 2 billion extra people by 2025, there has to be scope to reduce water conveyance losses and irrigation efficiency both in Australia and internationally.

Table 1. Surface water irrigation efficiency in three irrigation systems

Key indicators	Liuyuankou China	Rechna Doab Pakistan	MIA Australia
Area (ha)	40 724	2 970 000	156 605
Losses from supply system (%)	35	41	12
Field losses (%)	18	15	11
Net surface water available to crop (%)	46	32	77

In recent years, there has been a growing concern in Australia regarding the impact that major diversions of water for irrigation are having on the environment. This is creating further "economic" competition for water along with demands from urban and industrial users. Given that rural water users (predominantly in the irrigation domain) account for over 70 percent of Australia's total water use, a figure similar to that in most Southeast Asian countries, and given increasing physical scarcity of the resource owing to climate change and other environmental factors it is not surprising that pressure is increasing on irrigators to increase water use efficiency and to achieve "true water savings" by conserving water otherwise lost through non-beneficial evaporation or seepage to saline aquifers.

The key to achieving "real" and substantial water savings lies in the technical, economic and institutional assessment of water-saving options in a "whole of the system" context.

Figure 1 shows the water cycle in an irrigated catchment at different spatial scales. Key interventions for improving the sustainability of irrigation systems and achieving water savings are indicated by numbers in circles. These interventions are described hereunder:

1. Volume and regime of water extraction from river, water rights definition, trading and regulation of water rights use, improved distribution and control of water delivery to farms to reduce conveyance losses.
2. Volume and regime of water extraction from groundwater, extraction must be matched by catchment and river recharge, improved delivery to farms by reducing conveyance losses.
3. Volume and regime of subsurface drainage, improved management to reduce leaching and drainage to groundwater, reduction of salt load to groundwater through soil storage, improved interception of

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[1] Charles Sturt University and CSIRO Land and Water, School of Science and Technology, Locked Bag 588, Wagga Wagga, NSW 2678, Australia. E-mail: Shahbaz.khan@csiro.au

subsurface drainage water and re-use through bioconcentration and extraction, salt management schemes for subsurface drainage and groundwater.

4. Reduce water extraction through greater water use efficiency on farm by reducing deep percolation and evaporation losses.
5. Improved management of surface water drainage, improved re-use, reduction of contaminants.
6. Land-use management to control water yield and the amount of salt and pollutants directed to rivers and groundwater.
7. Adaptive irrigation management under climatic variability and change scenarios. Better weather and climate forecasts will help to reduce the rainfall rejection and end-of-system escape losses.

This paper describes the technical, economic and institutional aspects of water use efficiency studies focusing on interventions 1 to 5 for catchments in Australia. Modelling approaches aimed at extrapolating the impact of water savings on basin and country level food security and water balance are provided by Khan *et al.* (2005c, d).

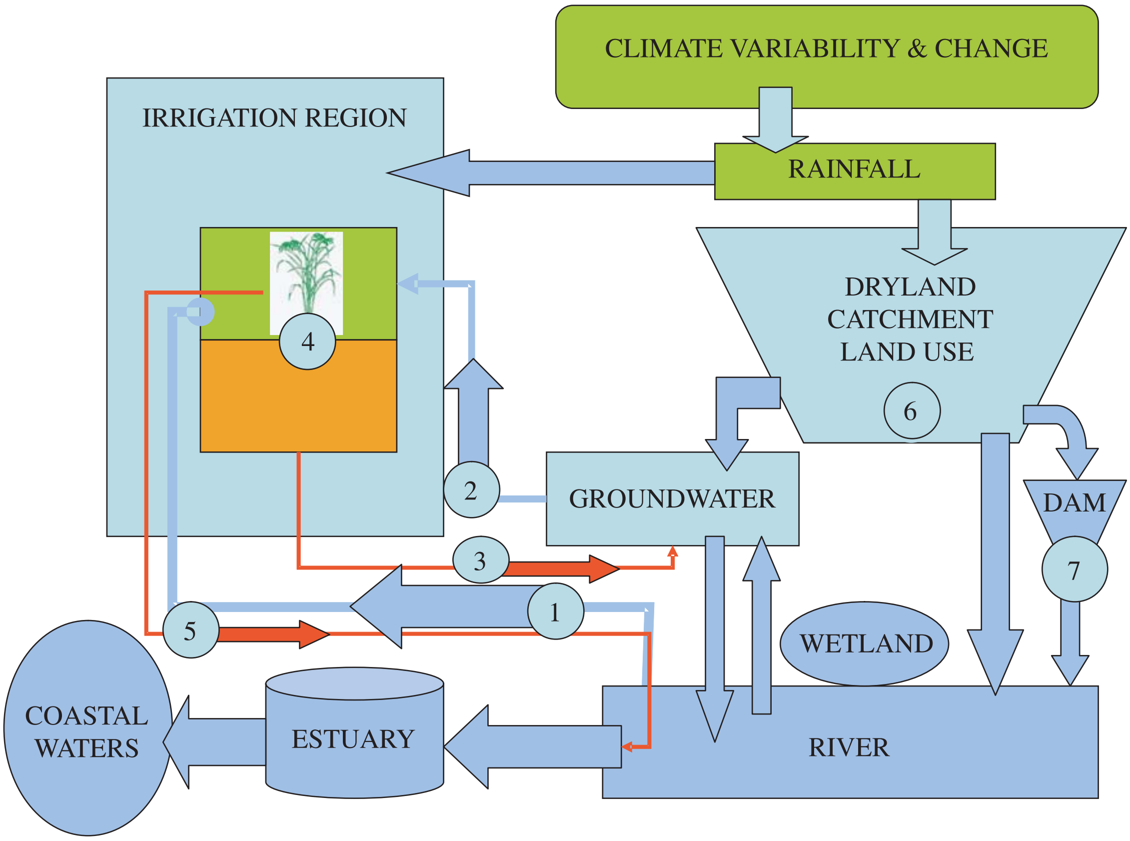

Figure 1. Schematic of irrigated catchments with key interventions (in circles)

2. Technical issues

It is imperative to save water to achieve higher productivity per unit of water consumed and to provide water for the environment. However lower commodity prices do not allow investment in higher technologies owing to government subsidies and international market competition.

Technical options for more efficient use of available water supply for irrigation include:

- Adoption of on-farm water-saving methods (from soil water monitoring to pressurized irrigation systems) to improve water productivity.

- Reducing conveyance losses in the water delivery systems through canal lining and piping.
- Matching water-saving investments with higher value cropping systems.
- Removing salinity constraints from farm to regional levels through efficient leaching of soils and promoting sustainable multiple use of water.

The relative economic and environmental merits of adopting these alternative water-saving options on overall water saving and water productivity at the irrigation system or catchment level are largely unknown due to a lack of integration of existing data sets. Therefore it is imperative to start identifying and filling in vital gaps. As a part of the Pratt Water Study (Pratt Water 2005) in the Murrumbidgee catchment, a targeted data-gathering, modelling and integration approach (Khan *et al.* 2005a, b) was adopted to evaluate alternative technologies for reducing over 300 GL (1 GL = 1 million m^3) on-farm and off-farm losses within the Coleambally and the Murrumbidgee irrigation areas.

2.1 System approach

2.1.1 Water-saving options at the catchment level

To identify "true" water-saving options it is important to adopt a system approach for accounting for all surface water and groundwater use, losses and interactions at the catchment, irrigation area and farm levels. An example of a system's water balance for the Murrumbidgee catchment level is shown in Figure 2.

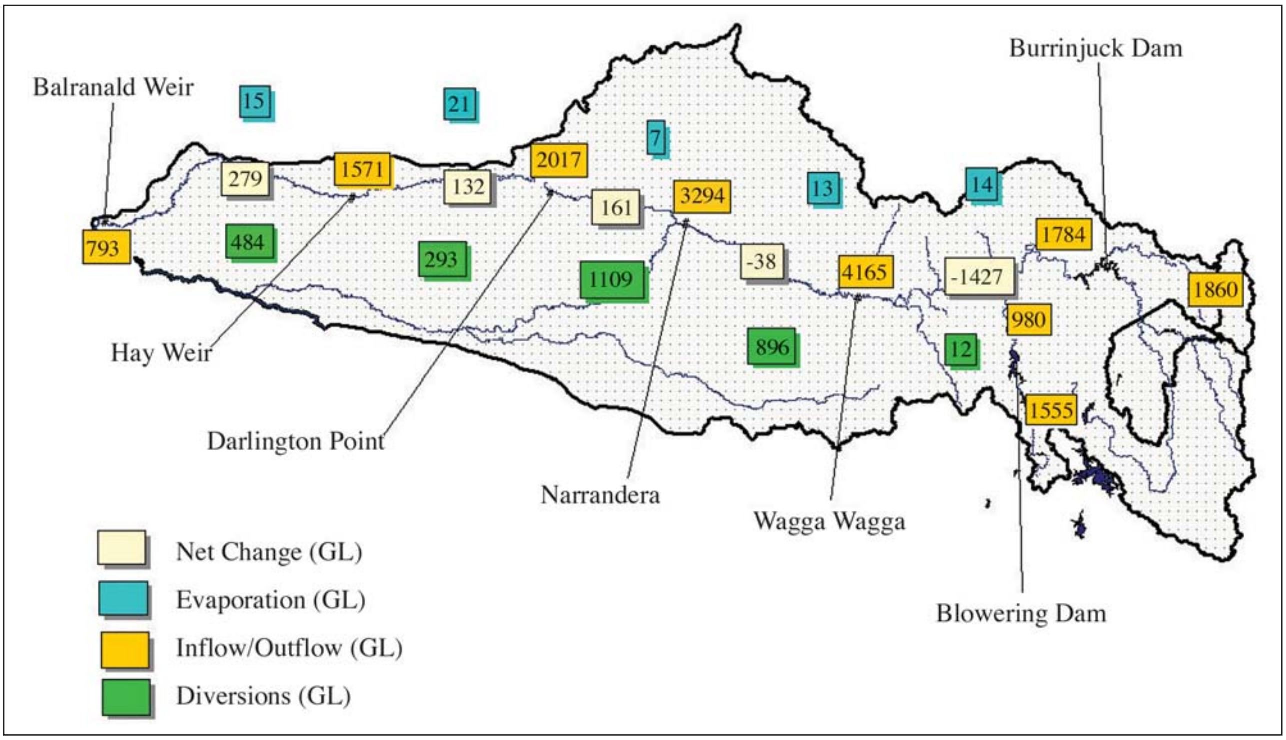

Figure 2. System's water balance at the Murrumbidgee catchment level

This analysis has shown unaccounted losses of greater than 300 GL in some of the river reaches (Khan *et al.* 2004b) which could lead to real water savings and better environmental management by investments in catchment management infrastructure.

2.1.2 Water-saving options at the irrigation area level

A similar system's approach at the irrigation area level provides indications of water savings at the whole of the irrigation area level. An irrigation system's water balance for the Coleambally Irrigation Area (CIA) is given in Figure 3 which provides a possible water use efficiency scenario for the CIA (using 2000–2001 water allocations). The water use efficiency at various points within the system is expressed in terms of water delivered versus the water supplied and net water use through evapotranspiration and the tonnes/GL of produce. Key water use efficiency indicators for the CIA show that irrigation efficiency in terms of root zone storage to the water diverted from the source is 70 percent. Unless there is an investment in irrigation infrastructure to improve measuring, monitoring and reduction of losses this efficiency indicator will remain low. The overall water use efficiency of the CIA is 77 percent due to capillary water use by the crops. In terms of production efficiency the CIA is at 343 tonnes/GL. Further analysis of the whole of the CIA water savings shows (Khan *et al.* 2004b) that it is possible to increase economic water use efficiency from US$91 000/GL to 97 500/GL and total water use efficiency from 77 percent to 84 percent under the current cropping and irrigation regimes.

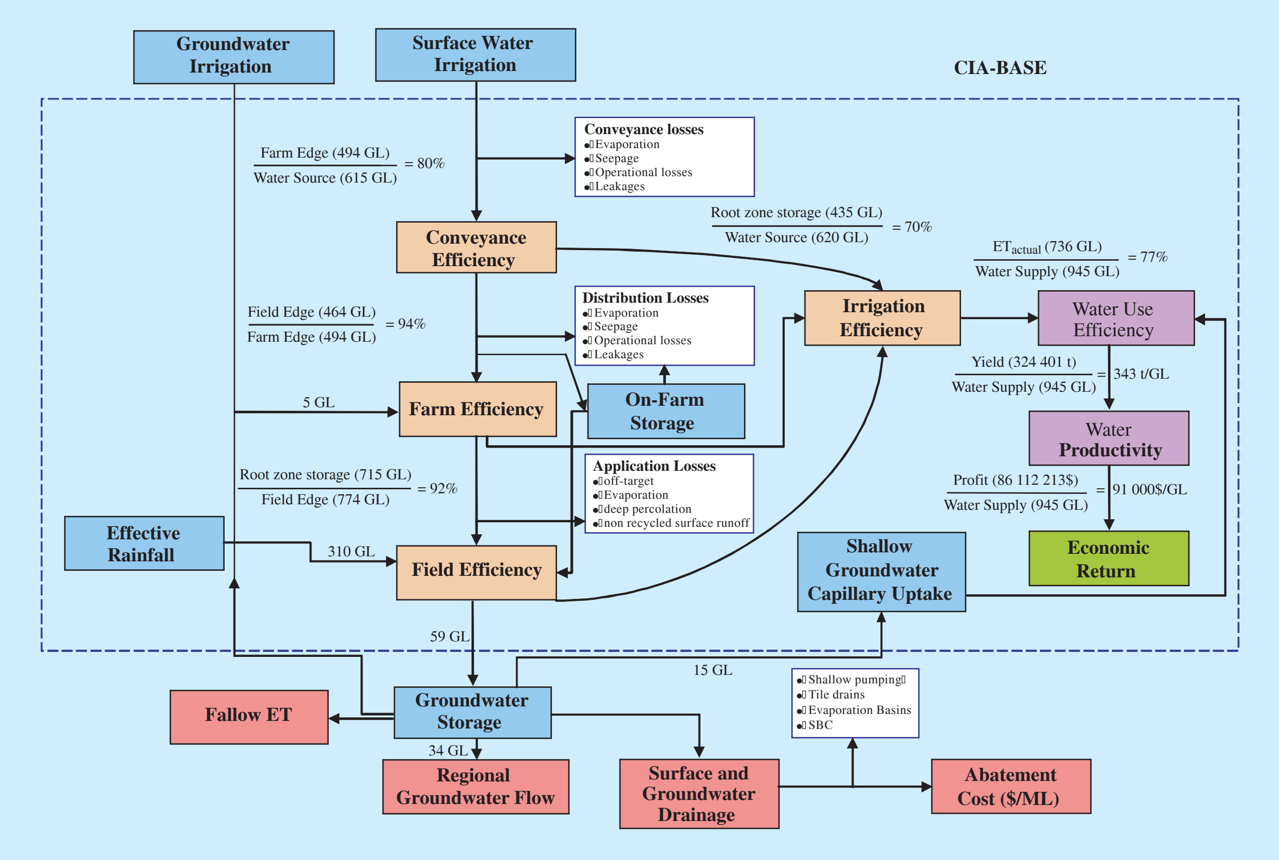

Figure 3. Base case water use efficiency of the CIA

2.2 Targeted water savings

2.2.1 Increasing on-farm water productivity

Table 2 provides an overview of the net crop water requirements (NCWR), current irrigation levels and yields in the MIA. In all cases (except for alfalfa) NCWR are well below the maximum reported irrigation application levels. There are major differences between minimum and maximum crop yields, as well as the overall amount of water consumed and the NCWR. These data clearly illustrate that there is a potential to increase farm profitability at a range of levels which include:

- Better matching of soils and groundwater conditions with cropping systems.
- Improving irrigation efficiency by 1 to 5 ML/ha.
- Increasing crop yields by 20 to 50 percent by removing the management, nutrient and salinity constraints.

Considering a range of soil, water and groundwater conditions, Khan *et al.* (2004a) concluded that on-farm irrigation technology conversions can provide potential water savings ranging from 0.1 to 2.2 ML/ha for different broad acre crops (Figure 3); for example, 1 to 2 ML/ha from flood to sprinkler and 2 to 3 ML/ha

Table 2. NCWR, reported water use and yields in the MIA (2000/2001 reported crop areas are used)

Crop	Crop area (ha)	NCWR		Reported irrigation[†] (ML/ha)			Reported yield (MT/ha)		
		(ML)	(ML/ha)	Median	Low	High	Median	Low	High
Rice	46 120	506 562	11	14	12	16	9.5	6	12
Wheat	39 215	111 835	2.9	2	1	3	5	3	7
Oats	2 896	7 512	2.6	2	1	3	3.5	2	6
Barley	3 034	8 615	2.8	2	1	3	5	2.5	7
Maize	2 924	18 813	6.4	8.5	6	12	9.5	6	15
Canola	2 685	4 643	1.7	2.5	1	4	2.5	1.8	3
Soybean	2 881	18 383	6.4	8	6	9	2.6	1.5	3.8
Summer pasture	3 929	45 154	11.5	7.5	7.5	8			
Winter pasture	24 184	50 403	2.1	5.5	5.5	6			
Alfalfa (uncut)	2 468	43 291	17.5	10	7	14	7.3	5	15
Vines	13 635	77 508	5.7	5	3	7.5	15	9	25
Citrus	8 700	68 861	7.9	7	4.5	10	38	20	60
Stone fruit	934	9 071	9.7	9	7.5	12	18	15	20
Winter veg.*	1 500	921	0.6	5	4	6	60	50	70
Summer veg.**	1 500	8 906	5.9	7	6	10	90	60	120
Alfalfa (cut)	0	0							
Total	**156 605**	**980 477**[‡]							

[†] Reported irrigations levels are subject to adjustment for measurement error, e.g. 14 percent accepted underestimation by the Dethridge wheels.

* The irrigation requirement and yield is for onion. For salad crops (lettuce), the irrigation requirement is 2–4 and yield is 30–40.

** The irrigation requirement and yield are for tomato. For melons, the irrigation requirement is 4–7 and yield is 30–40.

[‡] Reported gross diversions for 2000/2001 are 1 048 000 ML and on-farm deliveries are 857 000 ML.

Sources: Hope and Wright (2003); Beecher (1995); MDBC (1997); MIA & DLWMP WG (1997).

from flood to drip irrigation for citrus; 1 to 1.5 ML/ha from flood to sprinkler and up to 4 ML/ha from flood to drip irrigation for vineyards and 0.5 to 1 ML/ha for vegetables. Modelling simulations show water-saving potential of 7 percent for maize, 15 percent for soybean, 17 percent for wheat, 35 percent for barley, 17 percent for sunflower and 38 percent for broad bean, if on-farm surface irrigation methods can be replaced with pressurized irrigation systems.

Based on recent work by Khan *et al.* (2004a) the potential savings for converting from good surface water to pressurized irrigation systems (travelling irrigators or centre pivots or equivalent) are shown in Table 3.

Table 3. Water use and savings (ML/ha) for selected crops under different irrigation technologies

Irri. method ML/ha	Surface			Sprinkler			Water savings		
	High	Low	Av.	High	Low	Av.	High	Low	Av.
Maize	10.6	4.3	8.3	9.2	4.0	7.7	1.4	0.3	0.6
Soybean	6.6	3.6	5.4	5.6	3.2	4.6	1.0	0.4	0.8
Wheat	4.2	0.5	2.4	2.8	0.5	2.0	1.4	0.0	0.4
Barley	4.3	0.7	1.7	2.4	0.7	1.1	1.9	0.0	0.6
Sunflower	7.0	3.5	4.6	4.8	3.1	3.8	2.2	0.4	0.8
Broad bean	4.9	1.5	3.2	3.3	1.4	2.0	1.6	0.1	1.2

2.2.2 Measuring and managing water losses from supply channels

The study used a combination of geophysics and *in situ* measurement methods aimed at identifying seepage hot spots and the extent of overall water losses. In the Murrumbidgee catchment seepage measurements were made over 700 km of channels. Both sides of the selected channels were surveyed using EM31 meters. These meters use electromagnetic induction to measure the average electrical conductivity of the soil from the surface to a depth of 6 m. This average reading is known as "apparent conductivity". The EM method provides a quick way of gathering many data without any ground intrusion but is susceptible to interference from electrical or magnetic interference. Low conductivities indicate potential seepage sites.

Once the EM31 surveys were completed, maps were prepared from the EM imaging data using GPS-based locations. These maps helped to identify the parts of channels where higher seepage rates were occurring. Doppler flow meters were then used to measure inflow and outflow of hot spot reaches of channels to cross-validate losses from channels. At the high seepage sites, Idaho seepage meters were used to quantify seepage rates. In this method a cylindrical bell is pushed into the bottom side of a channel and is connected by tubing to a reservoir and gauge located on the water surface. As water seeps from the bell, the change in pressure in the reservoir is measured by the gauge.

EM31, Idaho seepage meter and groundwater lithology and quality data from a MODFLOW model were used to "train" an artificial neural network (ANN) model (Khan *et al.* 2004b). Once trained, the network can be used for predicting seepage rates in channels.

Study of on-farm conveyance losses on nine farms showed that seepage losses vary from 1 to 4 percent of the total water supplied which can be more than 60 ML/year (equivalent to 4 percent loss) for a studied farm.

Seepage losses computed for over 700 km of channels in the MIA showed that seepage losses were over 40 000 ML/year and evaporation losses were over 12 500 ML/year. The total losses in given channel reaches vary widely and can be from 1 to 30 percent of the water supplies and 0.2 to 9 percent per kilometre length.

Canal lining and piping options were considered for saving conveyance losses from channels.

2.2.3 Ladder of water savings

Possible on- and off-farm water savings can be summarized as steps of a ladder of increasing on-farm and off-farm water savings (Figure 4) and water benefits. It is important to recognize that some steps are prerequisite for the next water use efficiency level. For example, to realize on-farm water savings it is crucial to implement soil and groundwater and flow monitoring programmes, to ensure irrigation levels are being matched with the crop water requirement, at the same time considering conversion to sophisticated irrigation. Similarly, for realizing off-farm water-saving options, it is vital to know how much water is being delivered in space and time before piping/lining of channels. It is important to reduce the conveyance difference and narrow the wide gap between the gross diversions from rivers to deliveries on farm by installing state-of-the-art monitoring and delivery systems as a part of the modern irrigation infrastructure.

3. Economic issues

To target on-farm and regional water savings it is hypothesized that the marginal costs for saving irrigation water will increase with the volume of water saved and there is a possibility to formulate irrigation water-saving cost curves for traditional or alternative different irrigation technologies to help shift these cost curves to lower costs as illustrated in Figure 5. Figure 5 shows a simplified schematic of the marginal costs (MC) and benefits (MB) for the current cropping systems. X represents the current viable levels of water savings which can be shifted to the right through the low cost alternative technology.

Figure 6 shows capital investment and total water savings by sophisticated irrigation technologies in the MIA. Typical capital costs to save one ML of water vary from less than US$2 000/ML to over US$7 000/ML depending upon soil type, crop and irrigation technologies used.

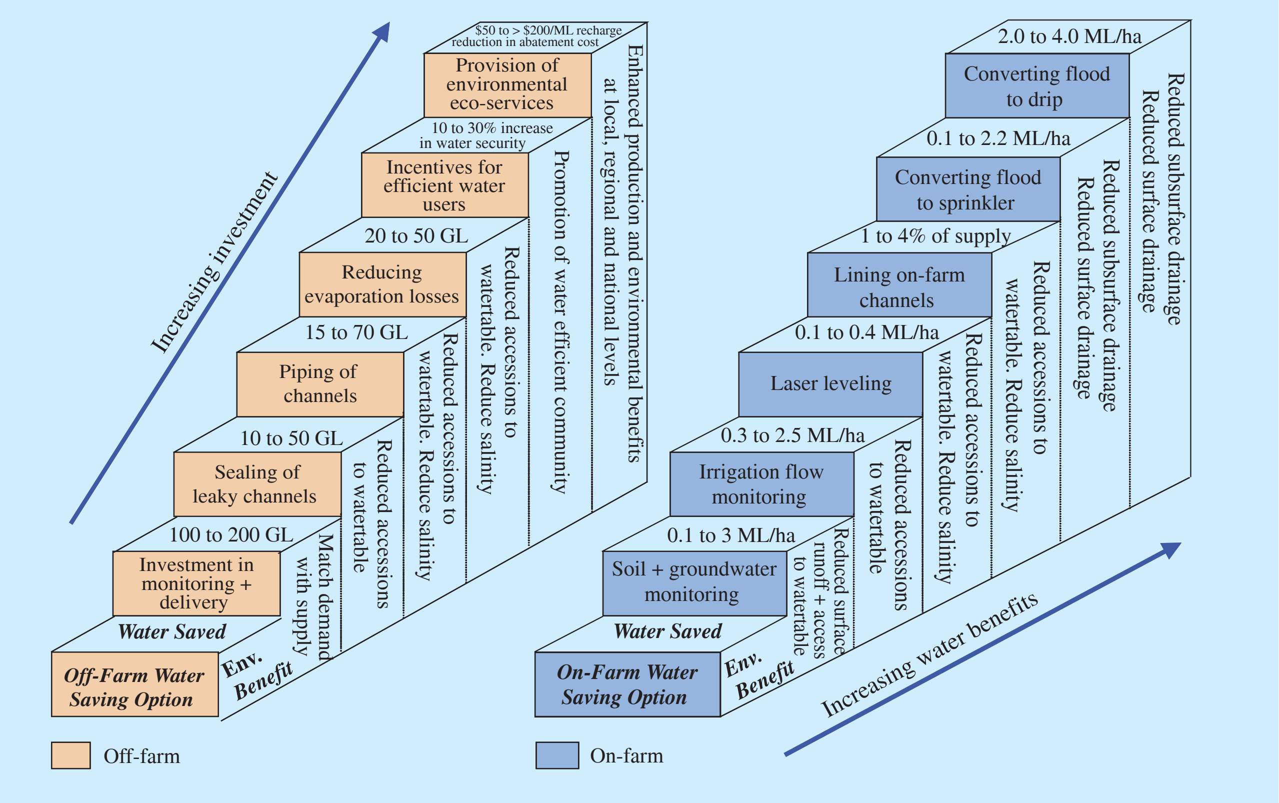

Figure 4. Ladder of possible water savings in an irrigation area

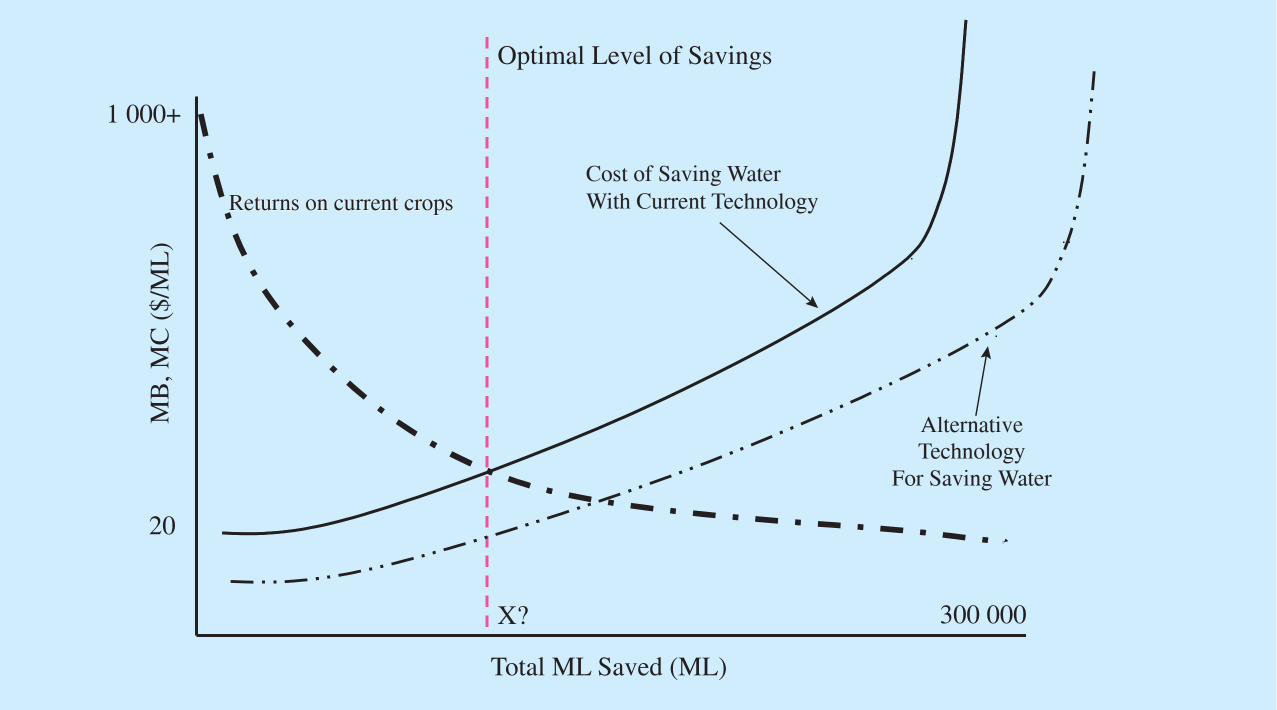

Figure 5. Cost–benefit curves for water-saving technologies

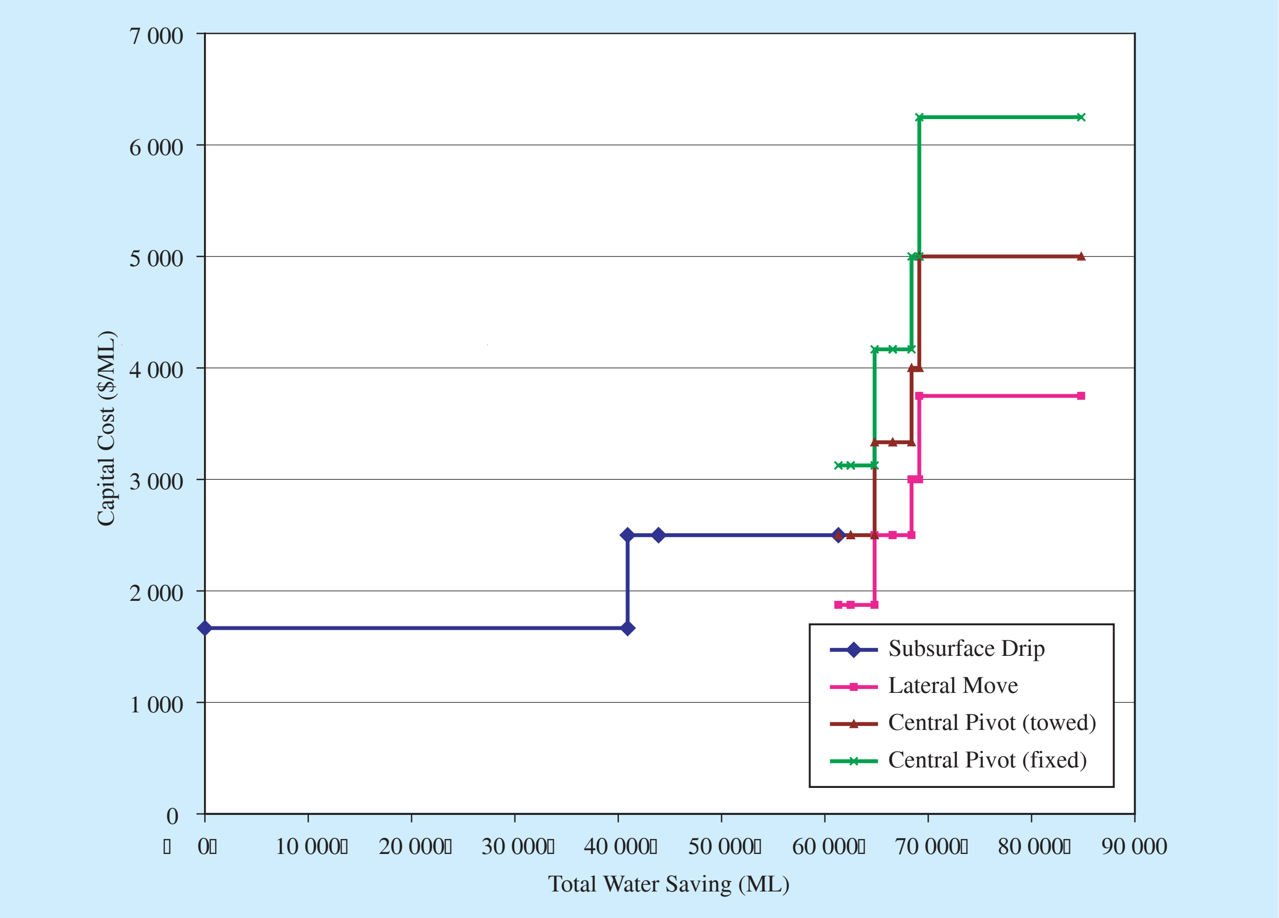

Figure 6. Capital investment and total water savings by sophisticated irrigation technologies in the MIA

Break-even analysis (not presented here) shows that the break-even years for conversion from flood to the pressurized irrigation systems are too long (greater than 15 years). There is a need to reduce the break-even period by considering leasing of water for the environment from farmers at around US$300/ML for a fixed period of five to ten years after which the water can be returned back to the farmer and the government can then lease the next lot of water from another group of farmers. This will help remove barriers to the adoption of irrigation technologies by moving farmers and irrigation areas to the next step of the irrigation efficiency ladder, reducing local and regional environmental impacts and securing water for better ecological futures.

The economic analysis of alternative water-saving technologies for channels showed that the cost of saving one ML of water increases with the total savings, as shown in Figure 7. Typical capital costs to save one ML of water vary from less than US$500/ML to over US$4 000/ML depending upon losses per unit length and the seepage reduction method used.

In Australia there is wide feeling that water savings which cost more than US$1 000/ML are not viable. The break-even analysis of different channel lining materials by Khan *et al.* 2004a shows that the price of saved water on an annual basis needs to be from US$30 to over US$200 to break even within the design life of the project. This investment can be achieved in two ways, by either using the saved water on higher value crops or by including saving costs as part of the overall water supply charges with a proportionate cost-sharing arrangement. For example, water delivery charges will increase by 5 to US$15/ML/season to provide water more efficiently. This will also reduce waterlogging and salinity abatement costs (current estimate for waterlogging and salinity abatement are US$10 to US$200/ML or recharge/year). The proportional cost to be paid by the farmer may be less than discussed here if it can be shared with the wider environmental beneficiaries. There is a need to promote a water efficient culture through “preferential rights of access” by providing a better level of security to farmers and irrigation companies investing in water-saving technologies.

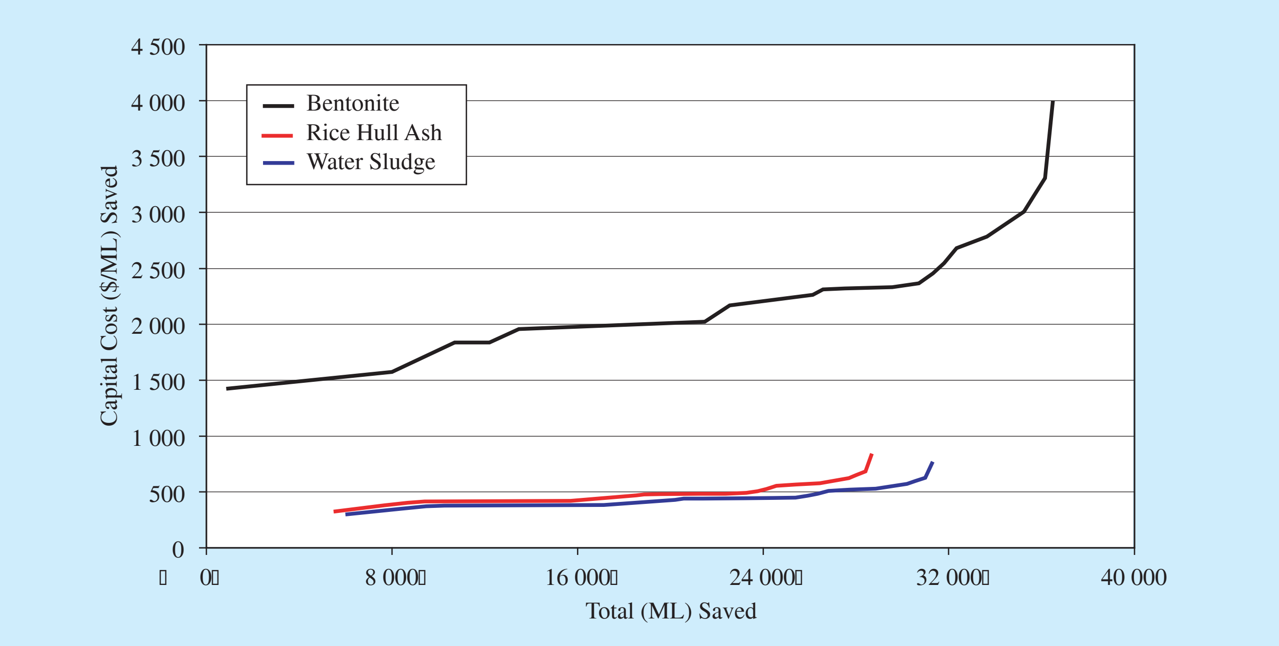

Figure 7. Capital investment curves for saving seepage losses

4. Institutional issues

4.1 Who saves and who owns the water losses?

One of the key impediments to achieving real water savings is the issue of ownership of losses and how to re-allocate on- and off-farm water savings. In New South Wales, conveyance losses are collectively "owned" by the farmers via privatized irrigation companies through a conveyance allowance. For example there is a provision in the Murrumbidgee Water Sharing Plan (Department of Land and Water Conservation 2003) for a conveyance access component for the Murrumbidgee Irrigation Company of up to 243 000 ML to make up for the transmission loss in water accounting (Clauses 26 and 40). Similarly farmers are given water entitlements irrespective of the actual crop water use. This water entitlement is used to irrigate crops which results in evaporation and deep percolation losses. If farmers invest in new technologies to save water losses they may like to increase their area of production or sell the saved water on the open market.

Institutional complications are caused by the common pool nature of the irrigation supply infrastructure and deep drainage below the root zone. This may lead to lack of collective action. Managing irrigation systems requires coordination among many users sharing the same resources of water and irrigation infrastructure. Users receiving the direct benefit are likely to ignore the effect of their actions on the common pool when pursuing their self-interest, therefore the environmental sustainability of surface and groundwater resources and maintenance of irrigation infrastructure risk a "tragedy of the commons".

To explore reasons for the lack of action by farmers and irrigation companies, reference can be made to the long break-even years (greater than 15 years) to achieve net profit from investment for conversion from flood to pressurized irrigation systems in the case of the Murrumbidgee Catchment. Farmers also have a lack of interest to permanently give up their water entitlements in exchange for capital incentives for new technology owing to uncertainty arising from current and proposed water reforms.

A business case for achieving water savings at the farm, regional and basin level has already been established by the Pratt Water Feasibility Study in the Murrumbidgee Catchment which asks for a uniform national water efficiency and environmental regulatory framework using the Council of Australian Governments (CoAG) framework (Pratt Water Group 2005).

Recently the Australian Government has initiated a National Water Commission (NWC) to drive the reforms more quickly. At the water distribution and on-farm level, the focus of reform and research is on:

- The identification and reduction of leakage and water losses.
- The determination of water benefits and improved water accounts (CSIRO, for example, has a US$20 million flagship project focusing on these and related water issues).
- Improved efficiency of water delivery systems, including the change over from gravity-fed to pressurized delivery systems and more optimal design of irrigation requirement and delivery to the root zone.
- The development of market-based instruments to facilitate improved natural resource management.

However, there are still major differences in productivity across farms, so considerably more effort is also required to identify the biophysical, management practice and social reasons behind this variability in order for all enterprises to work more productively.

5. Conclusions and way forward

In order to achieve true water savings, a system approach is necessary to target "real water savings" and to remove technical, economic and institutional barriers.

A system approach adopted in the Murrumbidgee Catchment showed accounted losses of greater than 300 GL can be saved (Khan *et al.* 2004a, b). The on- and off-farm water-saving costs vary from less than US$50/ML to well over US$5 000/ML. Such investments can be possible either by using the saved water on higher value crops or by including saving costs as part of the overall water supply charges with a proportionate cost-sharing arrangement. There is a need to reduce the break-even period by considering "leasing of water" for the environment from farmers at around US$300/ML for a fixed period of five to ten years after which the water can be returned back to the "owner" and the government can then lease the next lot of water from another group of farmers.

If the water saving technologies are considered on their own, costs involved will be prohibitive to result in any substantial investments by the individual farmers and irrigation companies. This is mainly because irrigation supply systems represent a shared and jointly owned common pool resource. There is the possibility of inaction among local, regional and national actors leading to market failure and a classic tragedy of commons. Institutional reforms aimed at minimizing risk of market failure driven by the tragedy of commons are required to secure a win–win situation for all stakeholders.

Due to lower commodity prices, farmers and irrigation companies on their own will be unable to achieve water savings. Unless water-saving costs and benefits are shared by all players in a catchment, "real water savings" are not possible. Private–public investment models aimed at providing "preferential access rights" to those who save water by investing in water-saving technologies may be one of the possible ways forward.

Acknowledgements

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Concepts and practices for optimal regional water resource allocation

Dong Zengchuan[1]

1. Water management

After the Second World War, natural resource exploitation increased significantly due to growing populations, industrialization and urbanization. This has subsequently compromised economic gains. Natural resources currently face huge pressure and many are almost exhausted with concomitant threats to livelihoods. Although natural water supplies are limited, demand continues to increase. Thus there is a need for sustainable regional development through careful management of water resources and monitoring of their relations with society and the physical environment.

1.1 Water resource use

Water is critical for maintaining all forms of life and supporting agricultural and industrial production. Its circulation method — the hydrological cycle — can be affected adversely by human activity.

Water has natural and social benefits so water resource management must take natural laws into account. Water use can be bifurcated into consumption and non-consumption modes. The main consumers are human settlements, agriculture and industry although they can contribute to restoring water balances. But water volumes have decreased and water quality has changed due to disruption of integrated ecological factors. If one is affected, the others will suffer as well, influencing the whole ecosystem. If water resources are depleted, lakes and rivers will shrink, desertification will occur and ground subsidence will result.

1.2 Water demand

Population rise and economic development exacerbate water demand. When average water availability per capita and natural water supply are low, sound demand management is the only option for sustainable regional development. The basic policies for demand management include: Restricting industrial production to conform with available water supply, the creation of a water-saving society, adjusting the water-pricing system, suppressing water demand and increasing sectoral water use efficiency.

1.3 Water resource systems

In the context of development and utilization, water resource projects comprise infrastructure and technical management units, which are interconnected. They address ecosystem and socio-economic management. Natural and artificial approaches can be used in combination to achieve desired results. With increasing water exploitation, artificial approaches have become more comprehensive in scale, structure and function.

2. Concepts for water resource allocation

2.1 Water resource allocation

How to allot water resources to meet societal and economic demand and avoid damage to ecosystems is a major issue, which supposedly can be resolved by rational allocation of supplies.

Such allocation should include: Equitable, efficient and sustainable principles; the use of mechanical or natural control measures, reasonable suppression of demand, guaranteed supply, environmental protection, temporal and spatial distribution of supplies among water use departments and promoting sustainable regional development. The substance of allocation is to deal reasonably with water competition among all users and to improve water use efficiency.

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[1] Professor, Hehai University, No.1 Xi Kang Road, Nanjing City 210098, China.

Various factors need to be considered for development practices:

(1) With respect to sustainable development, harmonize human and environmental co-existence.

For socio-economic development, water resources have to be utilized for human welfare but this can be juxtaposed by maintaining short- and long-term environmental balances. In this context, equitable allocation needs to be analysed with care.

(2) With respect to socio-economic development, consider equitable allocation and economic benefits.

Water resources must be utilized fairly to ensure social harmony. Therefore, when allocating water resources, equity and benefits must be simultaneously balanced to promote development.

(3) With respect to water resource development and utilization, supply and demand for water resources must be regulated.

A model for water resource development, utilization, protection and management needs to be researched; introduced technologies should be feasible, economical and environmentally safe. For water demand, ecological and industrial (structure and productivity) issues should be addressed, efficient water-saving technologies should be disseminated, increased water demand should be suppressed and adverse conditions should be accommodated. Regarding regular water supply, competition among water users should be coordinated, rainfall and groundwater should be subjected to careful husbandry and passive attitudes towards water distribution should be changed.

2.2 Models for water allocation

2.2.1 “Demand determines supply” model

This model is based on the concept that water resources are inexhaustible. According to predicted water demand on economic scales, water supply projects should be planned taking careful consideration of water requirements and avoidance of exploitation by overambitious schemes that interfere with river flow or incur desertification, ground subsidence and saline intrusion. If there is no water-saving awareness, application and dissemination of water-saving technologies will be difficult, generating waste and conflict between supply and demand.

2.2.2 “Supply determines demand” model

This model arranges productivity planning according to available water supply and industry structuring according to resource wealth; this is beneficial for protecting water resources. Water resource development is closely associated with regional economic development. For example, economic development enhances investment in water resources and the application of advanced technologies. Possible supply volume is also connected with economic development but exact volume is difficult to determine, so it is difficult to create a model for the development of regional economy in this respect.

2.2.3 Water allocation based on macroeconomy

The aforementioned models stress either supply or demand, isolate water resource demand from supply and neglect the dynamic coordination between water resources and the regional economy. Consequently the allocation theory for water resources, based on macroeconomy, is useful. It involves development of regional economy and a dynamic balance between demand and supply.

The relationship between water resource systems and the macroeconomy system is symbiotic. When water requirements grow because of regional economic development, the demand for water supply correspondingly increases rapidly and investment in water management infrastructure should be furthered. Hence, different sectors have to adapt to the degree and difficulty of water resource development. By analysing inputs and outputs, the water resource allocation theory takes account of the macroeconomy in order to realize coordinated development between regional growth and resource utilization. However it does not dovetail with sustainable development as regional growth may incur environmental pollution or potential ecological damage.

2.2.4 Sustainable development and water allocation

The main objective of water allocation is to balance resource, economic and ecological components. Sustainable water allocation adopts the strategy of coordinated development among the population, resources, environment and economy. While protecting the environment (including the water environment), it promotes economic and thus societal prosperity.

Sustainable development is an ideal model for water allocation, but needs further analysis.

2.3 Measures for water resource allocation

2.3.1 Engineering control measures

These measures involve rational storage, transfer and allocation of water resources. Temporal allocation addresses reservoirs, lakes and underground storage; spatial allocation addresses conveyance, river diversion works, canals, tubewells and pumping stations; quality regulation addresses: Clean tap water, polluted water treatment and desalination.

2.3.2 Economic measures

Establish a distribution and transfer model for rational water rights and rational water pricing, using economic factors, market allocation, preference for high efficiency water use areas and improved water use efficiency.

2.3.3 Legal and managerial measures

Allocation of water resources to water users via legal and managerial instruments.

2.3.4 Scientific and technological measures

Establish real time monitoring systems, scientifically analyse water demand, strengthen demand management, finalize decision-making, improve modernization of water resource regulation and rationally allocate water resources.

2.4 Water resource carrying capacity

As a result of the rapid economic development of industrialized countries, environmental pollution and resource shortages have become increasingly prominent; concomitantly, water utilization and demand have also risen sharply. From 1940 to 2000, freshwater extraction from rivers, lakes, reservoirs, groundwater and other water resources has increased fourfold. Unfortunately, many waterbodies and underground sources are severely polluted. Freshwater supply has diminished considerably. In many regions worldwide, freshwater pressure is becoming more and more intense and in some areas it is unavailable.

3. Scientific methods for rational water resource allotment

3.1 Sustainable development

Under the premise of protecting the environment, can the global economy keep growing sustainably? This is the issue of sustainable development. On the path to sustainable development, humankind has paid very high costs. There have been several representative stages:

1962: Rachel Carlson’s *silent spring* pondered how humans and nature can exist in harmony.

1972: The Club of Rome and *the limits to growth* postulated that without change in development models, sooner or later we will face development constraints.

1978: The Report of the Brundtland Commission, *our common future*, first proposed the concept of sustainable development.

1992: The United Nations Conference on Environment and Development and the Rio Declaration expanded the concept of sustainable development into a global strategy.

3.2 Engineering control measures for water resource systems

Modern water resource systems are generally: (1) Large scale; (2) multifunctional; (3) complex in structure. Therefore, systematic concepts and approaches should be used when analysing and resolving water resource issues.

A few key points are:

(1) Risk. Generally, decision-making looks to the future and predictions are not always accurate. There is a need to estimate decision-making risk.

(2) Multipurpose decision-making is often competitive; how can decision-making objectives be balanced?

(3) Scale. Decision-making is affected by differences in regions, cultural backgrounds and local people's benefits. Understanding this is important for effective coordination and implementation of water resource systems. Resolving issues needs to be done thoroughly and not in a piecemeal fashion.

3.3 Application of modern information technology

Do more to disseminate 3S (RS, GIS and GPS) technology, information transfer technology and decision-making support systems; comprehensively develop and adopt technology for water resource management and provide appropriate decision-making tools.

4. Suggestion

Shanxi Province experiences severe water shortages and the shortage trend has increased in recent years. With rapid socio-economic development in Shanxi, conflicts generated by water shortages are becoming more intense. There is an urgent need to: (1) Address exploitation for livelihoods and production by harnessing the Yellow River, surface and groundwater sources in order to realize their conjunctive use; and (2) form a new pattern of water resource utilization to meet socio-economic development demands. By doing so, the ecology of the water environment will improve.

There are a number of key characteristics concerning water resource allocation in Shanxi:

(1) Total water reserves are insufficient and temporal and spatial distribution is uneven; rainfall and floodwater inputs should be harnessed. Average annual precipitation in Shanxi is approximately 483 mm only and the average total volume of water resources annually is ±12.38 billion m^3. Average water availability per capita is 381 m^3, about one-seventh of the national average and considerably less than the worldwide average. Average water availability per hectare of cultivated land is 180 m^3, about one-tenth of the national average and much less than the worldwide average. Around 60 percent of the total annual precipitation is concentrated in July and August. Infrastructure capacity to harness rain and floodwater resources should be strengthened.

(2) Groundwater is severely overexploited and the ecological environment has deteriorated; groundwater overexploitation must be controlled and the ecological environment must be protected. Overexploited groundwater areas, centred around cities, approximate 10 600 km^2 and the overexploited water volume is about 0.7 billion m^3. Groundwater levels in Taiyuan City have dropped to 100 m and karst water levels annually drop by about 2 m.

(3) Water from the Yellow River can be used to efficiently increase regional water supply. Annual diversion flow is 1.2 billion m^3 for the Shanxi Wanjiazhai Water Complex on the Yellow River. Annual polluted water discharge is about 1 billion m^3. Coal mining does major damage to water resources.

(4) Disseminating water-saving technologies will improve water use efficiency.

5. Conclusion

Based on the Berlin Principle (good scientific practice), water resource management means: Without damaging the sustainability of important ecosystems, promote the coordinated development and utilization of water, soil and related resources to optimize socio-economic progress. In this regard, the following aspects are important:

(1) Humans and the environment can co-exist in harmony; water resources should promote economic development and the ecological environment should be protected and nurtured.

(2) Comprehensively consider and treat flooding, water shortage and water pollution problems.

(3) Examine engineering and natural options for developing infrastructure; build a water-saving society.

(4) Explore and apply theories on water rights, water prices and water markets, by means of government and market regulation models.

Guided by sustainable development, system theories, new technologies and rational water allocation, improve utilization efficiency and ensure sustainable regional development.

Water and irrigation management in the water-stressed Zayandeh–Rud and Karkheh River Basins, Islamic Republic of Iran

Nader Heydari[1]

1. Introduction

The Islamic Republic of Iran is located in one of the most arid regions of the world. Agriculture is one of the most important economic sectors accounting for 18 percent of the GDP and 25, 85, 25 and 90 percent of employment, food supply, non-oil products and raw materials used in industry respectively.

Aridity and drought are common nationwide. About 64.7 percent (105 million ha) of the country's total area experiences arid and semi-arid climates. Average annual precipitation is 250 mm and varies both spatially and temporally. The north, west and southwest regions cover only 30 percent of the country's total area but receive approximately 56 percent of the total rainfall. The central and eastern regions, which cover 70 percent of the country, receive the remaining 43 percent.

The world's available water per capita is 7 400 m^3/year. Generally when per capita water is reduced to 1 700 m^3/year or lower, the country or region concerned experiences different types of water stress. In the past, when I.R. Iran's population averaged 19 million, per capita water was about 7 000 m^3/year. Now that the population has reached 67 million this figure has been reduced to 1 910 m^3/year. Estimating population growth, it is predicted that by 2025 per capita water in I.R. Iran will be around 1 400 m^3/year.

Statistics reveal that I.R. Iran experiences drought twice every ten years (for example 1970–1971, 1972–1973, 1983–1984, 1998, 1999–2000, 2000–2001). Based on reports from 2001, drought affected more than 2.6 Mha[2] of irrigated agriculture, 4 Mha of rain-fed agriculture and 1.1 Mha of orchards.

The physical area is 165 Mha of which approximately 37 Mha are suitable for irrigated and dryland farming (20 Mha irrigated, 17 Mha dryland) — 18.5 Mha for field and horticultural crops (8.2 Mha irrigated farming, 6.4 Mha annually irrigated crops), 2 Mha for horticultural crops, 6.2 Mha for annual dryland crops and 3.9 Mha for fallow. The remaining 102.4 Mha include 90 Mha for pastures and 12.4 Mha for forests.

Due to water resource limitations, currently only 8.2 Mha are under irrigated agriculture which consumes more than 93 percent (84 BCM)[3] of total national water supplies (93 BCM). Currently the agriculture sector consumes 93 percent (84 BCM) of the country's renewable water resources (93 BCM) of which 46 percent comes from surface and 54 percent from groundwater resources. Overall irrigation efficiency is 40 percent, which is lower than the world average, but realistic with regard to total agricultural water consumption and the total irrigated area.

Currently, total irrigated agricultural production is 67 million tonnes and concomitant total water resources consumed amount to 84 BCM, i.e. for the production of one kilogram of crop, 1.25 m^3 of water is consumed. Estimate and planning analysis indicates that agricultural production should reach 186 million tonnes by 2025. Based on allocated water to the agriculture sector for the target year (93–103 BCM), the country should achieve water productivity (WP) of 1.6–2.0 kg/m^3. Based on the role of each unit of water consumed in national production, WP in I.R. Iran is quite low.

Statistics from 2002 reveal that irrigated land under regulated water (dams, diversion dams, river pumping) amounted to 3 Mha. Of this area, only 52.3 percent was equipped with main irrigation and drainage networks

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[1] Research Associate and Basin Coordinator for the CGIAR Challenge Program on Water and Food (CPWF) international project in the Karkheh River Basin (KRB), Irrigation and Drainage Department, Iranian Agricultural Engineering Research Institute (AERI), P.O. Box 31585-845, Karaj, Iran. Fax: +98-261-2706277; email: nrheydari@yahoo.com

[2] Million ha.

[3] Billion m^3.

and 21.6 percent was equipped with secondary irrigation and drainage networks. Out of 8.2 Mha of total irrigated lands, 4.2 Mha were not under secondary irrigation networks and over a small area, on-farm development activities (land levelling, land consolidation) were conducted. These are indicators of unsophisticated irrigation infrastructure activities compared to water supply activities. This causes extra water losses in the consumption phase.

Imbalances between investment and execution of water supply and water demand management programmes has led to lower irrigation efficiency and agricultural water productivity, through water losses, waterlogging and soil and water salinization. Reports indicate that the area of land with drainage problems increased from 16 000 ha in 1977 to 700 000 ha in 2003. The price of privately supplied agricultural water in I.R. Iran is much higher than the price that waterboard authorities charge farmers. In other words the government pays subsidies for agricultural water supply.

Agricultural product losses in I.R. Iran are high (up to 30 percent for fruits and fresh vegetables). Assuming an average agricultural product loss of 15 percent, irrigation water loss through agricultural product loss is estimated to be 12.6 BCM which is equal to 40 percent of all the water stored by reservoirs.

The two Ministries of Energy and Agriculture (called Jihad-e Agriculture) administer I.R. Iran's water resources. Research institutes (e.g. AERI, SWRI in the Ministry of Agriculture or TAMAB in the Ministry of Energy), research centres, water departments in universities and consultant engineering companies (e.g. Mahab-e Ghods) also have important roles in this regard. There are 49 research or education institutes related to water — 14 research institutes specifically target water research, 25 societies on water or agriculture, 47 consulting engineers and 178 irrigation manufacturing or design companies (especially for pressurized irrigation systems).

2. The Zayandeh–Rud River Basin

The Zayandeh–Rud River has been the lifeblood of Central I.R. Iran for centuries and is focused around the ancient city of Esfahan. In 1600 Esfahan was one of the ten largest cities in the world; it was sustained by irrigated agriculture using the waters of the Zayandeh–Rud. The city was the capital of ancient Persian kingdoms and remains the cultural heart of I.R. Iran.

2.1 Physical characteristics

Central I.R. Iran is typical arid and semi-arid desert. Rugged mountains of limestone and siltstone, devoid of vegetation, rise sharply from their surrounding alluvial fans built up by seasonal torrents. Most of the area has thin soil overlying the stony alluvial fans, providing little basis for economic enterprise other than rough grazing on the xerophytic vegetation.

Cutting across this monotonous landscape is the fertile valley of the Zayandeh–Rud (Figure 1). The river rises in the bleak and craggy Zagros Mountains that reach over 4 500 m, traverses the foothills in a narrow and steep valley and then bursts forth onto the plains at an altitude of some 1 800 m. However, the splendour of the river is short lived: Reduced towards the east by natural seepage losses, evaporation and more recent extractions for irrigation, urban and domestic uses, the river eventually dies out in the Gavkhouni Swamp, a vast playa of white salt that forms the bottom end of the basin, lying at an altitude of over 1 200 m (Figure 1).

The Zayandeh–Rud Basin (ZRB) naturally is a closed basin. The total length of the Zayandeh–Rud River is some 350 km, but it is the central 150 km of the floodplain to the east and west of Esfahan that provide the basis for intensive agriculture and large settlements. Along this strip soils are deep and fertile, predominately silts and clay loams, slopes are gentle, ideal for the culture of irrigated agriculture built up over many centuries. The river indeed forms an oasis in the desert.

The basin has a predominantly arid or semi-arid desert climate. Rainfall in Esfahan, which is situated at an elevation of 1 800 m, averages only 130 mm per year; most of the rainfall occurring in the winter months

Figure 1. The Zayandeh–Rud Basin (ZRB)

from December to April. During the summer there is no effective rainfall. Temperatures are hot in summer, reaching an average of 30°C in July, but are cool in winter dropping to an average minimum temperature of 3°C in January.

Annual potential evapotranspiration is 1 500 mm, and it is almost impossible to carry out any economic form of agriculture without reliable irrigation. The primary source of water in the ZRB is the upper catchment of the Zayandeh–Rud.

2.2 Irrigated agriculture in the ZRB

The pattern of reliable spring floodwater emerging from the mountains onto flat alluvial plains during the warm spring months makes for an ideal environment for irrigated agriculture in the region. It is little wonder that irrigation has for centuries provided the basis for productive and, at least until recently, sustainable irrigated agriculture. In all respects Esfahan was one of the world's classic oases, irrigated by diversions from the Zayandeh–Rud.

2.2.1 Traditional irrigation

Original irrigation developments relied on three different technologies: Diversions, lifting and tunnelling. The waters of the Zayandeh–Rud were diverted through stone and wood weirs into a complex series of canals that roughly paralleled the course of the river.

For several centuries there were well-established and complex rules for diversion of water from the Zayandeh–Rud. Scrolls dating from 1544 in the reign of Sheikh Bahai spell out water rights for different parts of the river. Almost all of these areas, irrigating several tens of thousands of hectares, remained more or less unchanged until the advent of the modern irrigation era in 1970. Few of the traditional technologies remain.

Modern irrigation, either in the form of large-scale gravity irrigation systems fed by large regulating weirs or electric or diesel-powered tubewells, accounts for almost all irrigation. Traditional canals have been absorbed into the large-scale systems, while many *qanats* (underground infiltration tunnels for obtaining water) have either fallen into disrepair or have been dried up by adjacent drilling of deep boreholes. These systems are entirely under the control of local communities and may total as much as 40 000 ha.

2.2.2 Modern irrigation

Modern surface irrigation started with the construction in 1970 of major diversion weirs at Nekouabad and Abshar, each diversion weir controlling both a Left Bank and Right Bank main canal (Figure 2). These weirs were designed and built by the same companies involved in the construction of the reservoir, thereby creating a coordinated approach to water control and management in the basin. These four systems have provided the bulk of irrigated agriculture for the past 30 years.

However, one large-scale traditional gravity system still survives, at Rudasht, the most downstream of the irrigation diversions (Figure 2). Even this is in its last years of operation as a new diversion weir has already been constructed and will replace the traditional weir as soon as new irrigation canals are completed. Basic information on irrigation systems in the ZRB is provided in Table 1.

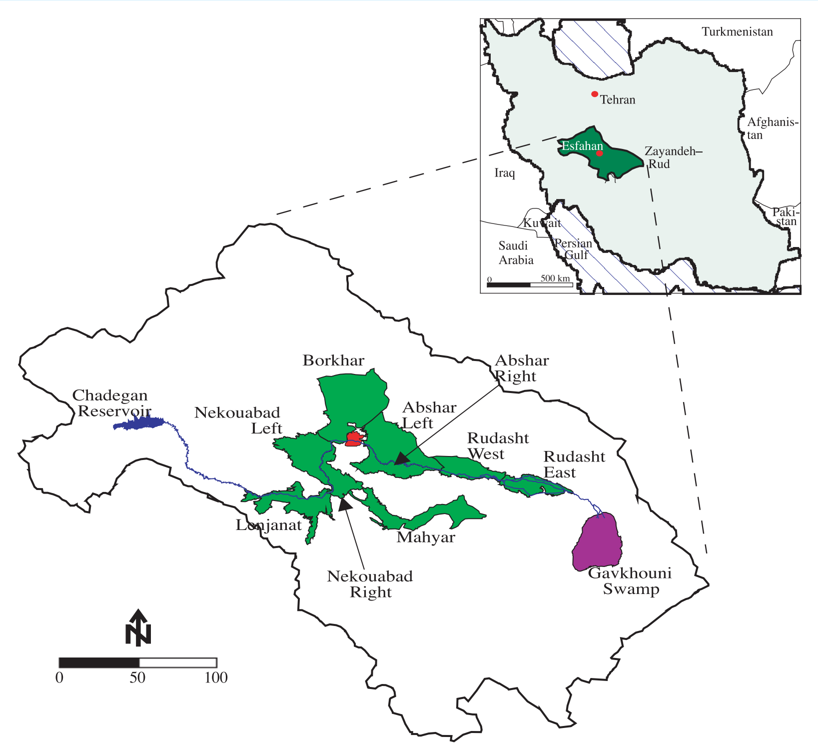

Figure 2. Location and main irrigation schemes in the Zayandeh–Rud Basin (ZRB), Islamic Republic of Iran

All of the gravity irrigation systems are based on modern design concepts brought to Esfahan by French engineers.

The two modern upstream systems at Nekouabad have no significant waterlogging or salinity problems and apart from a few locations where gypsum deposits create difficulties, there are few constraints to productive agriculture. Annual cropping intensity is about 170 percent, with slightly more land cultivated in winter than summer. The main crops in summer are rice, potatoes and vegetables while in the winter barley and wheat dominate. There are substantial areas of perennial orchards.

In Abshar, the middle reach of the modern irrigated areas, cropping intensities are lower, just over 100 percent, with only 32 percent of the area cultivated in summer. Constraints to good agricultural production are drainage problems towards the tail end reaches near the Zayandeh–Rud as well as some saline and gypsiferous soils. Rice is not grown extensively and there are no orchards. Summer crops are mostly maize and vegetables, while winter is dominated by wheat. Annual crops are mostly sugarbeet and alfalfa. Groundwater quality appears to be declining, and there is significant lowering of the groundwater table away from the Zayandeh–Rud.

Table 1. Basic information on irrigation systems in the Zayandeh–Rud Basin

Name of system	Date of construction	Command area (ha)	Design discharge (m^3/sec)	Length of main canal (km)	Length of secondary canals (km)
a) Old systems					
Nekouabad Right Bank;	1970	13 183	13	35.30	45.0
Nekouabad Left Bank;	1970	26 872	45	59.35	76.6
Abshar Right Bank;	1970	12 570	15	33.50	38.0
Abshar Left Bank	1970	23 000	15	36.00	33.0
b) New systems					
Borkhar	1997	18 500		29.00	Not finished
Rudasht Left & Right	(*)	47 000		209.20	Not finished
Mahyar	In progress	24 000		120.00	Not finished
c) Traditional systems		40 000			

* Rudasht is an ancient system being replaced with a new system. All new systems have conjunctive use of surface water and groundwater.

In Rudasht there is moderate to severe salinity and water tables are close to the surface. Cropping intensities are lower than Abshar, falling to 95 percent for the year and 28 percent in summer. This is in an area where significant volumes of groundwater are pumped but the water is low quality. Typically crops are wheat and barley in winter, some cotton and maize in the summer and annual sugarbeet and alfalfa.

The impact of the development of the four major irrigation networks at the same time as the construction of Chadegan Reservoir can be seen in Figure 3, which compares gross irrigated area in 1965 and 2000, as well as the shift in crop types.

The provision of more water with timing better suited to the needs of higher value crops has clearly been highly beneficial and productive at the basin level and for the upper portions of the irrigation systems. But it has had severe effects on the groundwater problems in the tail part of the system; this has led to greatly increased inequity in production and incomes between head and tail end parts of the basin. Head end farmers are perceived, perhaps incorrectly, as profligate water users, at the expense of tail end areas.

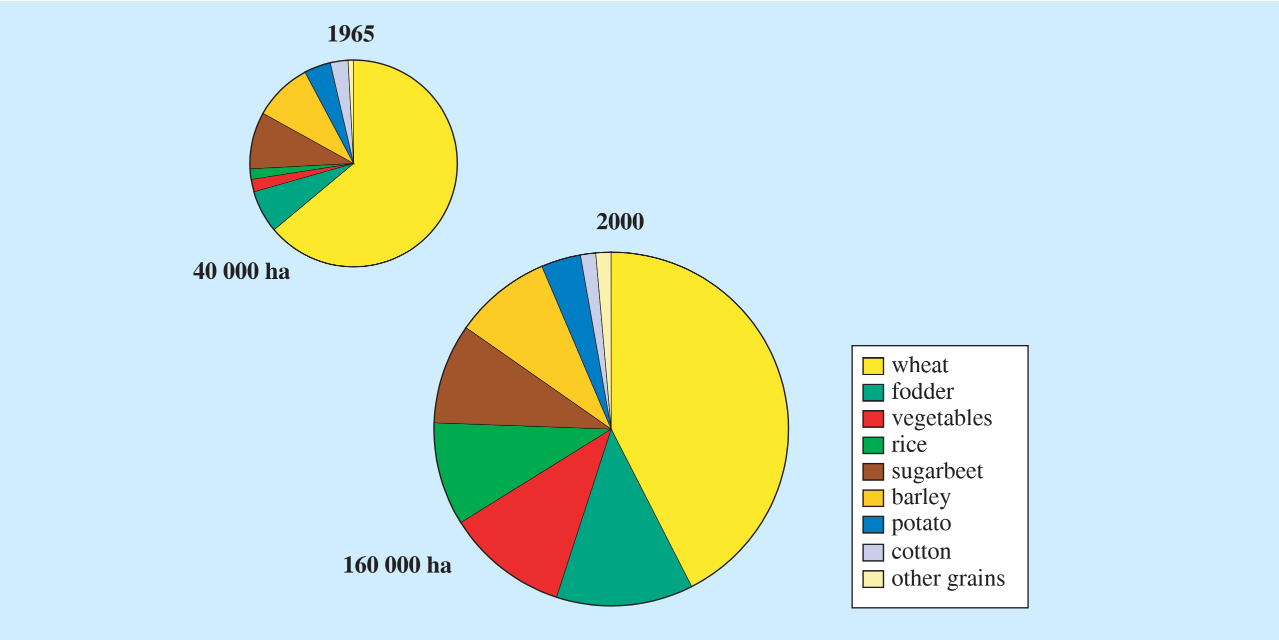

Figure 3. Changes in cropped area and cropping patterns from 1965 to 2000 in the ZRB

2.2.3 Recent irrigation developments

In the past few years there has been a large increase in the size of the gravity irrigation network. Two large systems have been constructed at Mahyar and Borkhar, while the Rudasht network has been modernized and a new weir has been constructed.

The Mahyar and Borkhar systems provide surface water to areas where there has been substantial groundwater irrigation for several years. In both areas the water table has been dropping and in Mahyar it is of particularly poor quality. The design intention is that surface water supplies are used by farmers (only to be delivered when annual water availability at Chadegan Reservoir is at or above normal levels) in times of reduced water stress to protect their groundwater resources.

Whether this happens or not remains to be seen. Farmers will clearly value good quality freshwater supplies more than their lower quality groundwater and may try to augment groundwater supplies rather than switch backwards and forwards from groundwater to surface water depending on canal availability. The risk in these areas is that if additional areas under irrigation are established because of additional freshwater supplies, more groundwater will be extracted in dry years to compensate for the lack of surface water supplies. At present cropping patterns in both areas tend to be rather low water-consuming crops: Grapes, sunflower, wheat, melons and millet. But it is possible that freshwater will encourage a switch to high value crops that have higher water consumption such as rice and alfalfa.

A second type of irrigation development has been expanding very recently in the reach of the Zayandeh–Rud between Chadegan Reservoir and Lenjanat. Traditionally irrigation was restricted to gravity use in these areas because of the deep valley in which the river runs. However modern technology has allowed the development of larger areas of fruit and nut trees by installing large diesel pumps along the river and pumping up the hillsides into terraces provided with drip irrigation. Initially the pumping was perhaps 20 to 30 m up from the river, but now huge pumpsets have been installed that pump water right up from the valley to the plains on either side. The current area may be in the order of 10 000 ha and is rapidly expanding. No doubt this type of irrigation development is and will be economic because fuel is cheap and the crops grown are high value, but the impact on downstream water users cannot be discounted.

It seems somewhat contradictory that while large-scale irrigation systems established 30 years ago, let alone the traditional systems that date back hundreds of years, are struggling to obtain sufficient water, new irrigation developments continue apace in the basin.

The ZRB has been experiencing water stress for the past 50 years. Expansion of the irrigated area through major investments in modern irrigation systems, the establishment of large-scale industries which require significant volumes of water and the continuing rapid growth of Esfahan, with a current population of over 2.5 million people, have all depended on the fragile water resources of the ZRB.

Since 1950, strategies have been adopted to increase natural water potential, both through transbasin diversions and reservoir construction. But by 2000 it was clear that demand had continued to grow faster than potential water resource development. As a result there is increased pressure on both water and soil resources. Tail end areas show the greatest stress with reduced water availability, deteriorating groundwater quality, increased soil salinity and declining agricultural production; little water reaches the environmentally valuable Gavkhouni Swamp at the tail end of the Zayandeh–Rud (Figure 1).

It is therefore impossible to avoid the conclusion that current levels of agricultural production are unsustainable under current management conditions.

The ZRB provides a classic example of a closed basin, one where all water is used up within its productive area. Under closed conditions, any change in water use within any one sector will inevitably affect all other water users in the basin and apparent improvements in one sector must be examined at the basin level to determine the impact on other sectors or on other users elsewhere in the basin.

This means that there is no single solution to the current water crisis: Changes at the farm level, system level or basin level undertaken in isolation will not be sufficient to alleviate the current conditions. While specific actions are required at each level, they must be integrated into a total basin-wide management strategy to be effective.

Under these conditions it is clear that some degree of radical thinking is required that will develop and implement a more integrated approach to the water problems of the Zayandeh–Rud. In attempting to move towards an integrated approach, the I.R. Iran–IWMI collaborative research project deals with water management issues at each of the three main management levels (field, system and basin) and then looks at policy issues that aim at integrating water management at the basin level (Murray-Rust *et al.* 2000; Salemi *et al.* 2000).

2.3 Field level water management issues

The I.R. Iran–IWMI joint research project concludes that there are still important gains that can be made in terms of water productivity if farmers adopt more effective on-farm water management techniques. These include better matching of water application to crop and soil water requirements, improved land levelling, correct furrow shaping, mulching, use of flexible polythene pipes for on-farm water conveyance and micro-irrigation.

However, modelling indicates that if farmers adopt all of these methods (and most can only adopt a subset of the improvements on any given farm) then water productivity will increase by a maximum of 33 percent over the next 20 years, from about US$0.12 to US$0.16. This is not a dramatic improvement on an annual basis and the gains must be offset by deducting the increased capital input and labour costs involved. Further, the higher benefits will likely only be obtained when farmers switch from lower value field grain crops to higher value fruits and vegetables and they cannot all do this unless there is a change in the overall marketing and processing sector.

The research also concludes that improvements in on-farm water management do not result in water savings when considered from the basin perspective. If a farmer uses less water through improved water management techniques, the water he does not use will quickly be used by other farmers. Water productivity will clearly be greatly increased, but it will not result in any amelioration in water shortages at system and basin levels.

There is a need for continued research on appropriate water management techniques for different soils and crops. However, the research so far concludes that the best way for farmers to adopt more effective water management techniques is for them to move into higher value crops wherever possible. Micro-irrigation techniques should only be actively promoted when the value of the crop is significantly higher than current cropping patterns because the capital costs of micro-irrigation are high and must be offset by growing more profitable crops.

The research recognizes that some farmers have already adopted a number of improved management techniques. It recommends that a socio-economic survey that includes both adopters and non-adopters be conducted to see what factors appear to encourage or discourage farmers in the adoption of potentially important water management techniques.

Deficit irrigation techniques also need to be promoted because these are an important response in years when water supply is lower than normal. However, supplies must be augmented in years when more water is available to offset inevitable increases in soil salinity associated with deficit irrigation.

2.4 Irrigation system level — water management issues

Despite the recognition that water is scarce throughout the basin and there is a need for improved management, the research finds some shortfalls in the overall information required to implement an effective programme of water management. The most important data that are lacking are accurate estimates of actually irrigated area and cropping patterns for each irrigation system. Without these data it is impossible to more precisely match water deliveries to individual irrigation systems to actual demand. As a result, irrigation deliveries to irrigation systems are largely determined by designed areas and cropping patterns and estimates of estimated potential evapotranspiration.

The research strongly recommends that major efforts be made to improve information on irrigated areas and cropping patterns using a combination of field surveys and remotely sensed data. Project results show it is not difficult to use satellite images to estimate irrigated area, crop type and actual evapotranspiration and the results are sufficiently accurate to guide managers and policy-makers.

Part of the problem stems from the historical division of responsibility for water and agriculture into separate departments. But data from both departments are essential for improved water management. The research strongly recommends that data be collected on the basis of the canal layout at main and secondary levels, rather than the current mix of water for canal levels and agriculture by administrative districts.

The research also strongly recommends the adoption of methods for benchmarking of irrigation performance at system and subsystem levels so that actual values of water productivity and matching of water deliveries to crop–water demand can be determined.

The research recognizes that there is a lack of useful data on groundwater use for irrigation, although the research results indicate groundwater use in major irrigation networks is significant. A survey is required of actual water use practices using both canal and groundwater by representative farmers, so that total water use for agriculture can be better estimated. This is important both because some surface water seeps into groundwater and is used effectively rather than being wasted and because groundwater levels in many irrigation networks are declining.

There needs to be a review of current water allocations between irrigation networks as well as within irrigation networks. Current allocations fall half-way between equality between networks and favouring head end systems.

The research shows that there are productivity increases at system and basin levels if water is used on the most productive soils, but this has negative implications for equity between head and tail end water users. The research also recommends special attention be paid to the new irrigation networks of Borkhar and Mahyar which are still being developed. Research suggests these networks are at high risk of soil salinization and groundwater depletion because the provision of modest amounts of good quality canal water may encourage farmers to pump even more that at present because they can mix poor quality groundwater in larger volumes.

2.5 Basin level — water management issues

The research concludes that agriculture will be the sector with the lowest overall priority. This means that whenever there are deficits in water below planned conditions, agriculture will take a disproportional reduction in water availability, as occurred during the 2000 and 2001 drought.

While recommending that further investigations be made that can help augment existing or planned water supplies, water resource developments cannot *per se* solve the problems of the basin and demand projections suggest that it will be impossible to find sufficient water to meet unregulated demand after 2020.

To make matters more complex, new irrigation developments in Mahyar, Borkhar and along the upper reaches of the Zayandeh–Rud seem to have been improperly evaluated in terms of actual water availability. This does not mean the developments are incorrect or inappropriate, but that their impact on other water users has not been properly evaluated. This is a clear example of the need for integrated modelling of water resources at the basin level.

The increase in groundwater pumping over the past ten to fifteen years is alarming. Although exacerbated by the recent drought, the overall trends for the past decade are declining water tables, increased installation of pump sets, deepening of boreholes and, in tail end areas, declining quality of groundwater. Despite these trends, there is no effective monitoring or regulation of groundwater exploitation at the basin level. The report anticipates long-term damage to groundwater resources throughout the basin unless an effective basin-wide groundwater monitoring and regulation system is established.

Parallel to this increase in pumping is the apparent continued increase in soil salinity. This is a broad trend from head to tail throughout the basin and in individual irrigation networks in the lower half of the basin. Increased pumping means that salts accumulate in soils without being properly leached.

The research finds that although there is much data available in individual departments and agencies there is no effective coordinated database that is a common public resource useful for integrated management purposes. Given the strong sense of the report that uncoordinated unilateral approaches are not the way to integrated water management, it is essential that data from different sources are made available to facilitate a more coordinated approach to water management.

A strong recommendation is therefore given for the development of an effectively coordinated and managed database that brings together information from all different sectors that can be used to support integrated water management at the basin level. This database then provides the basis for testing different models of water allocation and use into the future and developing appropriate management actions when water supplies are significantly different from average conditions.

2.6 Policy issues

The research stresses that while independent actions at field, system and basin levels can lead to improvements in water productivity, greater benefits will accrue if there are strong linkages between these different actions.

The report feels that there is a need to have a clearer and more transparent system of water allocation between sectors so that managers within each sector know how much water they will have each year. The allocation priorities should be based on demand under normal conditions backed up with modifications to be adopted in exceptionally dry years. Assuming agriculture is likely to be the lowest priority, some form of drought insurance scheme could be adopted to compensate for lost production in dry years.

The research strongly recommends that a basin level water management authority be established that has executive responsibility, rather than an advisory role. With water becoming increasingly scarce at the basin level in the foreseeable future so that changes in any one water use automatically affect all other water users, it is no longer possible to split management between different agencies. Instead, a provincially based water management authority has to play an active role in assessment and monitoring of water resources, allocation of water between sectors and close regulation of the water sector.

While accepting this is a complex and contentious proposal, evidence from other countries indicates that as water resources become increasingly stressed there is a need for increased central control over water resource management and regulation.

In the longer run, the research recommends that an aggressive policy supporting very high value crops, backed up by investment in agro-industrial processing is the best strategy for supporting farmers in the ZRB given the overall shortage of water. Low prices and low productivity of field grain crops make their widespread cultivation an ineffective and unsustainable use of scarce supplies of good quality water. Water productivity and farm incomes can only be improved by switching to higher value crops that use less water, such as fruits, nuts and vegetables.

3. Karkheh River Basin

The Karkheh River Basin (KRB) is located in the west to southwest of the Zagros Mountains at coordinates 56°34′ – 58°30′ north latitude and 46°06′ – 49°10′ longitude (Figure 4). The area of the basin (inside I.R. Iran) is 50 764 km^2 of which 27 645 km^2 comprise mountains and 23 119 km^2 are plains and hills. The mountainous areas of this basin are mostly in the eastern and central parts. The plains, which are mostly in the northern and southern parts, cover almost 45 percent of the basin area.

Figure 4. Geographical location and boundaries of the KRB

Based on hypsometric studies, 75 percent of the basin is located at altitudes of 1 000 to 2 000 m and 0.6 percent of the basin is above 2 500 m. Eventually the slope of the basin decreases and gently passes Hawr al Azim wetland, the outlet of the KRB.

Based on general hydrological classification of basins in I.R. Iran, the KRB is identified as one of the sub-basins of the Persian Gulf Great Basin. From the north, the basin encompasses the Sirvan, Ghezel Ozan and Gharachai Rivers, from the west the I.R. Iran–Iraq Border Rivers, from the east the Dez River and from the south up to part of the western border of I.R. Iran.

The pattern of precipitation in the KRB is Mediterranean. Rainfall in the basin is characterized by winter rain and then autumn and spring rains. Annual precipitation is 219 mm in Hamidieh (the southern part of the KRB) to 765 mm in the north.

The hottest areas of the basin are located in the south. The coldest areas are found at altitudes exceeding 3 000 m, mostly in the north and northeast.

Evaporation in the KRB varies from 1 800 to 3 600 mm depending on altitude. The average annual evaporation varies from 1 894 mm (in Mahidasht at an altitude of 1 350 m) to 3 561 mm (Abdol–Khan Station at 40 m).

The KRB has both surface and groundwater resources. In 1994 the share of agricultural water consumption from these resources was 3.956 BCM. Following completion of irrigation networks under the Karkheh Reservoir scheme, this was increased to 7.433 BCM (a 90 percent increase).

Both surface and groundwater are of good quality but the quality of groundwater in the southern plains has deteriorated slightly. Potential surface water resources in the KRB amount to 7.374 BCM. In wet years this can be doubled and in dry years it can be reduced by 50 percent.

The KRB encompasses one of the poorest regions of I.R. Iran. It has very inadequate infrastructure and was severely affected by the war with Iraq. Enhancing low food production under both dry farming and irrigation conditions is of crucial importance to increase farmers’ per capita income.

Two major agricultural production systems prevail in the KRB. Dryland farming occurs upstream and fully irrigated farming in some upstream zones and all downstream zones of the KRB. The dryland areas are well established and cover most of the basin’s arable land, occupying 894 125 ha; irrigated land occupies 578 862 ha but this is expected to expand by 340 000 ha with the completion of the Karkheh Reservoir.

The KRB is a water-deficient area and droughts are becoming a permanent feature. Due to water shortages and degradation of land and water resources, the livelihoods of rural communities are at stake.

In 1994, 3.956 BCM of water was used for agriculture in the KRB. Out of this amount, 36.8 percent was groundwater and 63.2 percent came from surface water resources.

Quantatively, the highest volume of groundwater is extracted from Gamasiab, followed by Gharasou sub-basin in the north of the KRB.

In the entire KRB area, the highest consumption of surface water resources occurs in the southern (lower) part.

Based on 1994 statistics, out of 4 157.4 MCM[4] of consumed water resources, 2 504.6 MCM (60.2 percent) was surface water and 1 653 MCM (39.8 percent) was groundwater. The share of agricultural water consumption in 1994 was 94.17 percent. Therefore the KRB is completely devoted to agriculture (industrial and mining activities accounted for just 0.32 percent of total water consumption).

3.1 Optimization of the Karkheh Reservoir Water Allocation Plan

The general objective of the plan is efficient use of Karkheh Reservoir water (in the lower KRB), considering technical, socio-economic, cultural and environmental parameters. The specific objectives of this plan are:

- Supply of water for 340 000 ha, KRB flood control.
- Generation of hydropower.
- Expansion of the irrigated area, taking into account proper cropping patterns, water requirements and enhanced irrigation efficiency.
- Supply of domestic and industrial water requirements in the long term.
- Optimized exploitation of surface and groundwater resources of the KRB, Meymeh and Doirej, taking into account the effects of water development plans executed in upstream areas.
- Livelihood improvements through employment opportunities in agricultural, construction and industrial sectors; overall socio-economic development in the region.
- The annual revenue of the region is planned to increase from about US$70 million to US$320 million and employment will rise from 25 000 to 70 000 persons.
- More reliable supply of water for existing irrigation networks and users of the system.
- Economic development via opportunities for industry and transportation.
- Potential opportunities for fisheries in the reservoir (with an area of 148 km^2) and also tourism and recreation.
- Possible export of water to neighbouring countries.

The plains' area addressed by the plan (340 000 ha) is located between Khuzestan and Ilam Provinces. The command area of irrigation networks and the area supplied by the Karkheh River include the northern part of the lower KRB (115 500 ha) and the southern part of the lower KRB (229 500 ha).

The plan has two phases:

- Study phase
- Construction and operation phases.

The useful life of Karkheh Reservoir, Hamidieh Diversion Dam and the diversion-regulation Pay-e-pol Dam is considered to be 50 years. The life for irrigation networks under dams is expected to be 30 years. Irrigation

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[4] Million cubic meters.

networks for Hamidieh, Zamzam and Ghods were constructed in the past and are currently operating. Table 2 lists phases of different plan components. Based on the information provided in Table 2 there is a considerable amount of work to do in the next eight to ten years, especially with regard to completion of the irrigation and drainage networks and efficient use of water for agricultural production in the lower KRB.

Table 2. Phases of the main components for optimizing the KRB water resource plan

Plan components	Study phase		Construction phase		Progress (%)
	Initiation	Complete	Initiation	Complete	
Karkheh Reservoir	1971	1993	1997	2000	100
Pay-e-pol regulating & diversion dam	1971	1998	1997	2004	70
Hamidieh Diversion Dam	–	–	1951	1957	100
Pay-e-pol main canal	–	–	1997	2009	30
Main networks of the Pay-e-pol plains (except Avan)	–	–	2004	2013	–
Avan Plain (main network)	–	–	1992	1997	100
Avan Plain (secondary network)	2001	2004	2004	2009	–
Dosalegh Plain (secondary network)	2003	2007	2005	2010	–
Arayez Plain (secondary network)	2005	2009	2007	2013	–
Bagheh Plain (secondary network)	2008	2009	2010	2013	–
Conveyance tunnel (Abbas Plain)	–	–	1997	2004	95
Main canal of Abbas Plain	–	–	2000	2004	–
Abbas Plain (main network)	–	–	2001	2005	–
Abbas Plain (secondary network)	2002	2005	2004	2010	–
Ein Khosh and Fakkeh (main network)	2003	2006	2005	2013	–
Ein Khosh and Fakkeh (secondary network)	2006	2010	2007	2013	–
Mosian (main network)	2007	2010	2005	2013	–
Mosian (secondary network)	2008	2010	2010	2013	–
Koosar (main network)	–	–	2000	2004	–
Koosar (secondary network)	2004	2006	2006	2009	–
Main canal of DA[†]	–	–	1998	2008	–
East of DA (main network)	–	–	1998	2011	–
East of DA (secondary network)	2004	2007	2007	2013	–
West of DA (main network)	1998	2004	2004	2011	–
West of DA (secondary network)	2001	2007	2006	2013	–
Main canal of Chamran	–	–	1998	2008	–
Chamran and development (main network)	1997	2002	2004	2013	–
Karkheh Noor and development (main network)	2003	2006	2004	2013	–
Chamran (secondary network)	2003	2005	2006	2012	–
Development of Chamran (secondary network)	2005	2008	2008	2013	–
South of Karkheh Noor (secondary network)	2005	2009	2007	2013	–
Development of Southern Karkheh Noor and northeast	2008	2010	2009	2013	–

[†] Dasht-e Azadegan region.

With more regulated flow to the Karkheh Reservoir due to construction of hydropower dams in the upstream basin and also revision of cropping patterns and improvements in irrigation efficiency (through modern irrigation techniques) it is expected that the cropped area could be increased to 345 000 ha.

Based on Phase 1 studies, water requirements for proposed cropping in areas downstream of Karkheh Reservoir are estimated to be between 14 500 to 20 050 m^3/s.

The proposed cropping pattern and relevant water requirements are based on the classification of the region into three areas. In this classification, homogeneity in parameters for soil and water resources has been considered.

Water resource development and availability of water for irrigated areas under the Karkheh Reservoir have been studied, taking into account water resource development upstream of the KRB and the environmental needs of the Hawr al Azim wetland.

3.2 Challenges for development of irrigated areas in the lower KRB

There are plans for at least 341 000 ha of land under the Karkheh Reservoir scheme to be irrigated through irrigation networks but there is a minimum water deficit of 18 000 MCM. Consultants' measures to overcome this problem are provided hereunder.

3.2.1 Construction of Azad and Javeh dams

I.R. Iran's water industry wants to construct Azad and Javeh dams on Sirvan River tributaries, because:

- Border waters will be exploited further.
- Transbasin diversion of water to Karkheh, Ravansar, Shahin, Nilofar, Sanjab and Mahidasht plains will provide more water for irrigation of agricultural land.
- Diversion of water from Sirvan River tributaries to the KRB can provide at least an additional 30 m^3/s to the Karkheh Reservoir inflows.

3.2.2 Optimization of water consumption and allocation in the KRB

Almost all projects in the basins of I.R. Iran, including the KRB, have excluded basin optimization. Research has been conducted at the project level not the basin level. Therefore, there is a need for I.R. Iran's water industry to analyse the KRB based on optimization of water resources and allocation at the basin scale. For the optimization, the following influences should be examined holistically:

- Conservation of national wealth (e.g. Karkheh Reservoir).
- Protection of the environment.
- Flood control.
- Agricultural development.
- Supply of domestic and industrial water.
- Agricultural production.

Also, the following questions should be answered:

- How many dams to build?
- How big should they be?
- How far should agricultural development extend?

There is a need to revise evaluation and estimates with regard to, *inter alia*, cropping patterns, water requirements, irrigation efficiency, percentage of water provided for environmental needs and the extent of expansion. Factors to consider are:

- Reduction of water consumption in the upstream areas of the basin.
- Reduction of water consumption in the west of country can have an important effect on agricultural expansion in downstream areas of the lower KRB.
- Optimization of cropping patterns in the plains and irrigated areas of the KRB.
- Changes in irrigation methods.
- Control of overflow of Karkheh Reservoir.
- Completion of irrigation and drainage networks under the reservoir.

3.3 Salinity and waterlogging in the lower KRB (Dasht-e Azadegan region)

The KRB is one of I.R. Iran's top-ranking basins. Despite overall potential in terms of climate, soil and water resources, agricultural water productivity in the lower and downstream areas of the KRB is very low. This is mainly due to the harsh climatic environment in the south and lack of sound agronomic, water and salinity management practices. In the near future 340 000 ha are scheduled to be irrigated under different irrigation networks. The lower part of the KRB region is typically hot and quite arid so agricultural production depends on irrigation. This area is planned for further development in line with the adjacent model of Dez irrigation district.

Waterlogging and soil salinity are the major threats to water productivity and sustainable agricultural production in the lower KRB; thus guidelines based on sound and relevant research are urgently needed. In addition to the national food security objective, improving the well-being of the agricultural communities in the mentioned lower region is exceptionally important to minimize socio-economic problems related to local migration of farmers and security issues among the I.R. Iran–Iraq border communities.

Major factors causing soil salinization in the lower KRB can be classified as follows:

- High groundwater table.
- Saline layers.
- Inadequate drainage facilities.
- High evaporative demand.
- Salt intrusion by wind.
- Sediment transport in flood periods.

The Dasht-e Azadegan region (DA) is one of the main plains in the lower KRB. Karkheh River diverts towards the northwest of the region near the city of Hamidieh and eventually joins the Hawr al Azim wetland. The DA region is located to the furthest south across the delta of Karkheh River, 20 km west of the city of Ahwaz. The total area is almost 200 000 ha, 95 000 of which spread over the current civil projects of the DA region. This plain is located between 47′55″ to 48′30″ east and 31′15″ to 31′45″ north and its height above sea level varies between 3 to 12 m. The main physical constraints include salinity and sodicity of the soil, high levels of saline groundwater, soil permeability and drainage restrictions. In fact, almost all of the farmlands in this region have salinity and sodicity problems. The results of semi-detailed soil survey studies indicate that approximately 80 percent of the farmland of the DA region has both low or high salinity and sodicity; statistics indicate:

- 1 percent or 70 ha have no salinity and sodicity problems.
- 16 percent or 14 599 ha have moderate salinity and sodicity.
- 27.4 percent or 25 040 ha have high salinity and sodicity.
- 2.2 percent or 2 040 ha are areas with varying rates of salinity and sodicity.

Available data and surveys show that the problem of soil salinity in the DA is magnified due to lack of farmers' knowledge and skills and unavailability of new and improved farming practices. Generally, the main cause of soil salinity in the lower KRB is the high water table, often less than 2 m, usually 1.2–3 m below the soil surface. If unaddressed, the problem is likely to worsen with the current plans for the expansion of irrigation networks.

Although main drains have been constructed in the area, they are not functioning properly. This is mainly due to technical problems (e.g. slope of the drain) and also problems concerning the outlets. Gravity drainage to outlets is not possible and pumping is required.

4. Conclusions and recommendations

During the past 20 years, and especially in the first, second and third five-year national development acts, many activities have been irregular or unsystematic. However, in recent years, huge investments have been made in the construction of dams and new irrigation and drainage networks. Unfortunately many of the projects were mostly development-oriented and less attention was given to their operation and maintenance. This factor, as well as rising costs, gradually reduced the performance of irrigation networks and has been juxtaposed by land drainage and salinization problems.

Fortunately at the end of the second national development act and especially in the third act, the problem was raised and special focus was put on the need for water management and improvements in the operation and maintenance of irrigation projects. This governmental concern has continued into the fourth five-year national development act.

To promote efficient water use, in the past decade, institutes have been improved in an attempt to enhance the management and planning of water resources, different water laws and the organizational structure of water. Different laws have been developed by the government and approved by parliament. Among the most important national acts is the “Equitable Distribution of Water Law”. Also different infrastructure activities both in the government and private sector have been developed and executed.

However, water organization in I.R. Iran still needs improvement, modification or new structure, especially with respect to recent drought indices.

To achieve efficient water use, the Ministries of Energy and Agriculture have initiated linkages and cooperation. However despite some progress, it appears that close linkages, or even transfer of water management authority from one ministry to another, are not sufficient solutions for the optimum use of water in I.R. Iran. Therefore we should have a new vision for water management and its organization, based on new international policies and concepts for water management, to make our policies and decisions more dynamic and comprehensive.

Efficient water use and improvements in agricultural water productivity (at least double the present volume) must be addressed in the next 20 years. This challenge needs innovative laws and institutions for water management and more participation by stakeholders in parallel with infrastructure activities (e.g. completion of irrigation networks, on-farm development activities), capacity building and applied agricultural engineering research.

Specific conclusions and recommendations for the ZRB and KRB basins are provided hereunder.

4.1 Zayandeh-Rud Basin

Basin development is normally a three-stage process with a relatively smooth transition between exploitation, water supply management and optimized allocation. The experience of the ZRB shows a much less encouraging picture. Increased water supply in each phase of development still fell behind demand growth. This is why in the past 50 years, the basin has remained generally water stressed. There is no interbasin integrated water management that distributes water in times of shortage uniformly between different uses, or even within a particular water use. The implication is that the basin will remain vulnerable to unsupplied demands and deficits of more than 10 percent will lead to significant stress in downstream areas.

The need for a more integrated approach to basin management as well as a set of long-term plans for re-allocation of water among sectors is therefore required to cope with the anticipated water deficits that will arrive in or around 2020.

Without transbasin diversions, the ZRB would not be able to meet existing and upcoming demand for water. The growth rates assumed are all modest: With annual growth rates of 20 percent per decade in all sectors the basin will be experiencing major deficit before 2020. Once supplies drop below historic averages, however, agriculture will take a significant cut in water supplies. If total supplies are only 10 percent below average then even in 2020, the most favourable year in the developed scenarios, total water supplies for agriculture will be less than those at present. So rapid growth must be decelerated or plans will have to target certain sectors to give up their share of water to other users.

The following technical, policy and research issues should be considered for water and irrigation management in the ZRB:

Technical issues at field, system and basin levels

Field level

- Promoting more productive farm level water management practices.
- Micro-irrigation.
- Deficit irrigation.

System level

- Measurement of actually irrigated areas.
- Irrigation performance assessment.
- Allocation of water between networks.
- Water allocation within irrigation systems.
- Conjunctive use of canal and groundwater.
- Special attention for new irrigation networks.

Basin level

- Water resource development.
- Groundwater monitoring and regulation.
- Soil salinity monitoring.
- Monitoring and development of a coordinated central database.

Policy issues that relate to various aspects of water management

- Drought insurance schemes.
- Water allocation between sectors.
- Establishment of a strong Basin Water Management Authority.
- Effective regulation.
- Training.

Research issues that require further study and investigation

- Water pricing.
- Crop pricing.
- Water rights.
- Water trading.

- Additional out-of-basin transfers.
- Moving towards agro-industry.
- Trading in virtual water.

4.2 Karkheh River Basin

Soil salinity and waterlogging, in addition to other weaknesses in agricultural water productivity improvements, are the major constraints in the lower KRB. The problems are physically related (soil, hydraulic gradient), but are mainly human-induced and can be managed by proper measures, including infrastructure activities (hard) and to a greater extent by improved water management (soft).

Hard option: Irrigation and drainage networks are developing in the area, but to date are mainly limited to the main canals/drains; lower order canals/drains that are necessary for the implementation of proper water management are lacking.

Soft option: Many studies and network designs (at the project level) are being conducted by consultant engineers and expert organizations; however these are mostly classic studies and application of new approaches and tools, such as the use of proper models relevant to various levels, are lacking or not applied sufficiently. This weakness is also evident in comprehensive plans for the basin.

Detailed studies are conducted mainly at the project level. There are no detailed or semi-detailed studies for the basin level. There is a critical need for clear and well-defined strategies and policies for water management in Khuzestan Province, through which two-thirds of the country's water flows, and especially in the KRB.

Wetland interactions with upstream irrigated agriculture developments could be optimized and managed using proper planning and coordination inside and outside the country.

Water limitations and all of the aforementioned issues suggest that we should efficiently use water in the KRB and the policy for water productivity improvement in the KRB should be given higher priority.

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Water resource allocation in China and implications for the local environment

Pei Yuansheng[1]

1. The need for water resource allocation

As a basic natural resource and an important strategic resource, water is vital for socio-economic development and environmental protection. To some extent, water availability has already become an important constraint in deciding whether the future economy of a country and region can develop quickly and whether societal status remains stable. Currently, freshwater deficit has become a worldwide issue and China is no exception. There are two main reasons for water shortages: Decline in natural supply and improper water use development strategies.

1.1 Water shortage in China

Spatially, water is more abundant in the south and east and in short supply in the north and west — water distribution is uneven. The distribution of annual precipitation is also non-uniform and in most areas four months of continuous rainfall account for approximately 70 percent of the total annual volume. Each year there are major fluctuations in rainfall so in some years volume is high and in others low, resulting in shortages.

1.2 Improper water resource development strategy

Due to socio-economic development, the demand for water is growing daily. Driven by economic interest, some areas have paid much attention to water demands from various sectors; the environment has subsequently been neglected and ecological degradation has resulted. Consequently sustainable socio-economic growth has been threatened.

Water use efficiency also differs among sectors. More water may be directed to the industrial sector to maintain the economy but at the expense of other areas and uniform water supply. On the other hand, among some basins or regions, due to poor management and inequitable allocation, downstream production and water demand have been neglected so upstream users can improve their lives; thus the downstream environment deteriorates, water use efficiency is low and local water usage is uneven.

In the industrial sector scenario, attention was given to water resource development and usage, but neglected water-saving exercises and protection. Moreover massive sewage discharges occurred in waterbodies without any treatment, seriously polluting local freshwater that may have otherwise been used, thus exacerbating the water shortage situation.

The Chinese Government now realizes the need for water allocation strategies and the development of water conservancy societies to promote healthy and stable socio-economic development and protect the natural environment.

2. Equitable water resource allocation strategy

Eqitable water resource allocation means "in the scope of a basin or specific region, conforming to efficient, fair and sustainable principles, using various engineering or non-engineering measures, following market economy rules and resource allocation criteria, employing various methods and measures including judicious demand control, safeguarding effective supply, maintaining and enhancing the natural environment and distributing different available water sources among regions and water departments". The goal is to foster benign distribution, satisfy socio-economic and ecosystem water demand, obtain optimum benefits from limited

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[1] Water Resources Department of China Hydroelectric Scientific Institute, Beijing 100044 China.

supplies and promote sustainable development. Therefore water resource allocation should follow the “3E” decision-making mechanism for social justice (Equity), economic efficiency (Efficiency) and ecological protection (Ecology) in order to address coordinated socio-economic and environmental development in terms of time, space, quantity and quality.

However it is not advisable to pursue only one goal. Considering equity but neglecting efficiency and ecology will not result in the effective allocation of water resources. Likewise, singular implementation of the other Es without their counterparts will also fail to produce results. Therefore they need to be balanced in order to realize sustainable development.

3. Influences of water allocation strategies on ecology

Given the significant influence of water resource allocation on the ecological environment, the region’s water resources and socio-economic status, China has developed or is carrying out water resource allocation strategies and has obtained relatively good results. Examples of these strategies at basin and transbasin levels are provided hereunder.

3.1 The Heihe Basin

In the Heihe Basin precipitation is scarce, evaporation is intense and water resources are in extremely short supply; these constraints generate anomalies among basin economies and ecologies, in middle reaches and downstream areas as well as interprovincial governance. Because the Heihe Basin encompasses Qinghai, Gansu and part of Inner Mongolia, benefit adjustment is complex and the basin management issue is prominent. Therefore, an authoritative, highly effective and coordinated basin management system must be established and water resources should be managed and deployed uniformly; the main thrust is equitable allocation. In order to resolve these problems and ensure socio-economic development and ecological rehabilitation in Heihe Basin, in April 1996, the Ministry of Water Resources established the Heihe Basin Administrative Bureau. After governmental authorization, in January 2000, the bureau officially started its mandate in Lanzhou City. With regard to the water use situation in Heihe, a water allocation strategy for the basin was proposed. Headstream protection via afforestation was the objective for the upstream area; water-saving enhancements in large-scale irrigation areas were implemented for the middle reaches; the third goal was maintaining the natural environment of the downstream areas — traditional water usage and grazing methods had to be altered to protect the natural vegetation.

Under this strategy, the volume of water needed for the middle reaches has been assured; by 2010 downstream groundwater levels should be restored to their former levels in the mid- and late 1980s. The water volume entering East Juyanhai can be maintained annually and West Juyanhai also has administered water levels. The overall ecological environment of the basin has been improved, but it is noteworthy that, after water-saving measures had been implemented in the middle reaches, the groundwater level dropped and the ecology degenerated. These issues need to be researched and resolved.

3.2 The Ningxia region

Ningxia is located in the arid and semi-arid area of Northwest China; annual precipitation is scarce, evaporation is intense and local water resources are in extremely short supply. The Yellow River has become the important water source to support socio-economy and to maintain the natural environment. At present, demands related to industrial and agricultural production and for human welfare in the Ningxia Chuan area and Yanghuang irrigation area can be satisfied and there is no critical water deficit. But in the southern mountainous area, precipitation is scarce and there are no large rivers. Agriculture basically depends on rainfall and local water deficits and soil erosion are serious; thus the ecological environment is extremely frail. According to our research, although the present water supply for the Ningxia Chuan area may be satisfied, owing to future socio-economic development, industrial water demand will increase sharply. If no water-saving measures are taken, water shortage in the Ningxia Chuan and Yanghuang irrigation areas will climb because of lower available water from the Yellow River; irrigation peaks and water deficits in the southern mountainous area could reach as high as 18.5 percent. Therefore, water-saving infrastructure needs to be implemented comprehensively, and saved water should be transferred to industrial and Yanghuang irrigation areas. Wastewater treatment should be upscaled in basins of the southern mountainous area, the Jinghe River Diversion Project should commence and human and livestock drinking water facilities to guarantee potable water supply in rural should be realized. Artificial water supply should be expanded to remedy problems generated by water-saving measures such as water table drop and ecological deterioration. With respect to future water shortages, the South to North Water Diversion Project should be taken into account.

Under this allocation strategy, the Ningxia Chuan area will not experience severe shortages, deficits in the southern mountainous area will be alleviated considerably, the water shortage rate will be curtailed to 12.1 percent and water distribution will be equitable. Future supplies for industry, agriculture and domestic water will be assured in Ningxia. Available water supply in the southern mountainous area may increase, carrying capacity may be enhanced and rural water supply may be guaranteed. Through artificial means, we can maintain the stability of lake surfaces in the region.

3.3 Transbasin diversion — the South to North Water Diversion Project

The South to North Water Diversion Project is a significant strategy to alleviate basin water anomalies in China. The north lacks water, but it is abundant in the south. Via the project, we will transport water from the Yangtze River to water-deficient areas such as the Yellow–Huaihe basins, the Jiaodong area as well as the northwest inland river area to alleviate the chronic water usage situation and to maintain the natural environment. After many years of planning and discussion, three water diversion lines have been formed (the east line, the median line and the west line) to connect with the Yangtze, Yellow, Huaihe and Haihe Rivers. Currently, east and median line projects have already begun and the west line project is being planned. The huge water diversion project will inevitably exert profound influence on the ecology of the source area and that of the receiving basins. In line with our research on the Haihe River Basin reception area, we have established three water resource allocation options: (1) Without the Project, continue the present water resource development plan including maintenance of the present water transfer activity (deep and shallow groundwater exploitation to meet socio-economic consumption needs as far as possible); (2) without the Project, apply water resource development with environmental protection being the core mandate and stop groundwater exploitation of deep and shallow layers, restoring ecosystems such as lakes and wetlands; (3) with the Project, by 2010 and 2030, guaranteed water supply to the Haihe River Basin will be 6.93 billion m^3 and 10.33 billion m^3 respectively.

If we continue with option 1, the Haihe River Basin ecosystem will suffer irreversible harm and regional economic development will be unsustainable. If we adopt option 2, then socio-economic development will be restricted considerably without an external water supply. Therefore, if the Project is not carried out, in ten to 30 years, the Haihe River Basin will be torn between economic development and ecological protection and will be unable to realize sustainable development. If the Project is constructed, water supply conditions in the basin will change with concomitant improvements in the environment and effects on socio-economy.

4. Conclusions

Equitable water resource allocation is an important tool to coordinate competition among basin water users, local users as well as departmental users. The cases of basin allocation (Heihe), regional allocation (Ningxia) as well as transbasin allocation (the South to North Water Diversion Project) indicate that water allocation has a profound influence on the ecological environment. If the allocation is appropriate, it may sustain the environment, otherwise it may damage or cause the loss of ecological functions. Therefore water resource allocation must have a macroscopic strategy, focusing on equity, efficiency and ecological protection, as well as a view to the long term.

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