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THE AUSTRALIAN WATER PARTNERSHIP

Consumption-based water management

State of the art in Asia

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Contents

Boxes

Figures

Preface

Consumption-Based Water Management distils and expands on the findings of an expert consultation hosted by Food and Agriculture Organization of the United Nations (FAO), and the China Institute of Hydropower and Water Resources Research (IWHR), 29-30 October 2019. The meeting brought together Chinese and international experts to discuss the technical, governance and other dimensions of managing consumptive water use and to understand the implications of more than ten- years pilot experience of consumption-based water management (CBWM) in China, particularly its potential for application in a broader range of climatic, political, administrative and socioeconomic contexts.

The publication aims to provide policymakers and experts with an understanding of CBWM so that they may consider whether it may – or may not – be possible to apply it in irrigation dependent parts of Asia that are currently experiencing, or are expected to experience, overextraction of water resources, in particular groundwater. The authors make clear that the implementation of CBWM requires preparatory work in developing water accounts, water rights, water allocation processes and associated institutional arrangements, and the science and practice of the estimation of evapotranspiration using remote sensing and provide useful ideas on all of these.

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Executive summary

Water scarcity and rising competition for water are facts of life in semi-arid and arid parts of South Asia and West Asia and are emerging, often in localized hotspots, in Southeast Asian countries with high but seasonal rainfall. The main drivers of rising water scarcity are population growth, food demand, associated economic development and changing dietary preferences. Climate change will further exacerbate water scarcity by affecting both the pattern and amount of water resources that can be extracted sustainably for human benefit. Water development in Asia has typically overlooked the importance of environmental flows to sustain aquatic ecosystems from upland catchments to the coastal zone and this has had evident and undesirable impacts on society. Water consumption and use for both environmental purposes and for irrigation are large compared to the needs for drinking water, sanitation and industry. The quest for sustainable water use therefore revolves around balancing irrigation demand with environmental needs and requires careful monitoring of actual consumption.

This document on consumption-based water management (CBWM) distils and expands on the findings of an expert consultation hosted by FAO and the China Institute of Water Resources and Hydropower Research (IWHR), 29–30 October 2019. The meeting brought together Chinese and international experts to discuss the technical, governance and broader dimensions of managing consumptive water use, and to understand the implications of more than ten years' pilot experience in China and its potential for application in a broader range of climatic, political administrative and socioeconomic contexts.

The purpose of this document is to provide policymakers and experts with an understanding of CBWM so that they may consider whether it may – or may not – be possible to apply it in irrigation-dependent parts of Asia that are currently experiencing, or are expected to experience, overextraction of water resources, in particular groundwater.

The focus of CBWM is to manage actual consumptive use of water in agriculture over space and time, understanding that the patterns of water flow and use are complex across a river basin. Accounting for consumptive use, rather than water delivery alone, allows estimation of water that is not consumed and which contributes to the supply of other downstream users and maintains river flows and health, through return flows to streams, rivers and groundwater.

The key concepts underlying CBWM are: (1) that water can be consumed either beneficially as crop transpiration resulting in food production, or non-beneficially, as evaporation from bare soils or bare water surfaces; and (2) the return flows that are not consumed may either be recovered for beneficial consumption, locally or further downstream in a river or groundwater basin, or be unavailable for further economic use if they flow to a sink such as saline groundwater or to the sea where water is required to support coastal and marine ecosystems.

In Asia and elsewhere, there has been much effort to improve irrigation efficiency in the expectation that water can be saved for reallocation elsewhere (more irrigation, urban and rural water supply and, rarely, environmental use). In practice, there are many documented cases of increased water use where high efficiency irrigation methods have been applied.

Increasing technical irrigation efficiency, by definition, means that a greater fraction of the water delivered is used in crop evapotranspiration (ET) and should result in greater crop production, which in turn increases farm productivity and associated income. Unless there is a properly enforced limit (also known as a quota or cap) on the water that can be consumed at the basin scale, farmers will inevitably use more as they seek to maximize production and income. The consequence is that the beneficial return flows that previously constituted part of downstream water users' established supply are diminished and/or that return flows that contributed to environmental water use are lost.

The administrative and technical challenges of reconfiguring a water allocation system based on consumption, rather than water delivery, are wide-ranging and require considerable evolution in policy and governance arrangements, especially in ensuring compliance in actual water use at both individual and basin scales. Formal water allocation processes are hard to find in Asia and are not supported by effective water accounting because of the sparse hydrometric networks and discontinuous volumetric measurement of variable (typically poor) accuracy. Outside the two pilot river basins in China, there are no river basins in Asia where a limit on water use has been implemented.

Chapter 1 provides contextual information, including the option of CBWM as a practical means to address the paradox of irrigation efficiency which, as described above, tends to result in increased diversions unless a properly enforced limit on basin-wide diversions is in place. It reflects on water scarcity in Asia – both now and as projected over the course of this century – and highlights the risks for human beings and the environment if water governance is not drastically improved in the decades to come, with a view to securing sustainable water use under the hydrological changes resulting from global warming.

Chapter 2 introduces the technical basis for CBWM. In summary, CBWM is demanding in terms of technical, managerial and institutional effort and can only be considered when water accounting and allocation procedures are already established and there is a basin- level cap on allocations.

Water accounting and allocation as currently practiced in China is exemplified in pilot projects in the Hai River Basin (north China Plain) and Turpan Prefecture in Xinjiang. Groundwater mining in the Hai River Basin has resulted in water use that is 130 percent of sustainable water availability across the whole basin. Rebalancing to sustainable water use is being managed through a combination of interbasin transfer from the Yangtze River and the Yellow River (the south–north transfer) and the implementation of a quota system to limit agricultural water consumption, particularly from groundwater. The quota system starts with a basin-wide cap on water abstraction, a reservation of water needed for important economic and social uses (cities, industry, power, drinking water supply and sanitation) and the specification of quotas for agricultural water use at province, prefecture and county and township levels, right down to individual (pilot) groundwater districts.

CBWM has been developed and adapted to fit within this general approach to water accounting and allocation. It makes extensive use of: (1) remote sensing (RS) technology to estimate consumptive demand, in conjunction with historical analysis of actual evapotranspiration and cropping data; and (2) hydrological modelling to specify consumptive use quotas, which are then monitored routinely using remote sensing.

Chapter 3 takes a closer look at law, policy and governance. Water scarcity is widely considered to be a crisis of governance rather than one of physical water availability. Any technical or theoretical solution needs to be practically implemented and must therefore garner wide stakeholder endorsement.

Meaningful discussion of CBWM must not only contemplate the regulatory framework required to facilitate such a technically sophisticated method of water management, but also the broader governance and administrative challenges associated with its actual implementation. The greatest experience with CBWM is in China, where the political, legal and administrative arrangements are quite different from those in place across the rest of Asia and the Pacific. The level of technical expertise is also very high, both within operational agencies and in the research organizations that support them. The examples given in this chapter mostly concern Chinese experience, but it is clear that systems of water management cannot be transferred from one country to another without considerable care and adaptation. The discussion emphasizes that there are no simple recipes.

Chapter 4 provides some step-by-step detail on the implementation of CBWM and gives a brief introduction to the principles behind the remote sensing techniques involved in the estimation of ET from cropped and natural land surfaces, at a range of scales from river basin to individual irrigation systems.

Chapter 5 discusses water scarcity and governance in Asia in more detail. Against this backdrop, it brings together the key findings in the preceding chapters and highlights the challenges and opportunities associated with attempting to implement CBWM in different Asian contexts.

The main conclusion is that the implementation of CBWM requires preliminary steps in developing water accounts, water rights, water allocation processes and associated institutional arrangements, all of which are very relevant and immediately necessary in most countries in Asia.

Chapter 1. Introduction

1.1 Background

This consumption-based water management review evolved out of an expert consultation held in Beijing on 29–30 October 2019. Coordinated by the Food and Agriculture Organization of the United Nations (FAO) and the China Institute of Water Resources and Hydropower Research (IWHR), the two-day meeting brought together 23 experts in a range of disciplines and from a variety of organizations. Drawing on their experience in remote sensing, economics, irrigation engineering and law and policy, the group discussed the technical and broader governance dimensions underpinning consumption-based water management (CBWM), the benefits of implementing CBWM in water scarce nations and regions, and the enabling conditions required for it to be successfully applied in different contexts.

In addition to presentations by each expert in attendance, a draft guide was prepared in advance by FAO and IWHR to facilitate discussion. Entitled Consumption-based water management: learning from experience in China, it focused on China's experience in developing and applying CBWM in two river basins with severely over-extracted groundwater resources, namely the Hai River Basin and the Turpan Basin in Xinjiang.

The draft guide set out the technical elements of the CBWM system that had been developed in China with a particular emphasis on remote sensing technology (which is required to estimate water consumption, otherwise known as evapotranspiration (ET). It briefly outlined the broader legal, policy and institutional settings framing CBWM in each river basin, as well as noting some of the challenges or barriers associated with developing and implementing such a system.

Ultimately, the long-term goal of work undertaken in the Hai River Basin and in the Turpan Basin in Xinjiang is to use CBWM to reduce groundwater extractions to a sustainable yield. In the case of the Hai River Basin, this goal is being met by a combination of demand management and supply augmentation from the eastern route of the south-to-north water diversion project, including the Chiang Jiang River (Yangtze) to the Yellow River.

1.2 Purpose and use of this document

The purpose of this document is to inform policymakers, experts, and stakeholders in irrigation-dependent parts of Asia that are currently experiencing, or are expected to experience, overextraction of water resources, in particular groundwater. It draws on extensive research which demonstrates why traditional assumptions regarding the benefits associated with irrigation efficiency are flawed and explains why CBWM may be a viable alternative capable of generating genuine water savings at the basin scale. It also outlines the technical capability and governance arrangements required for CBWM to be successfully implemented, as well as some of the challenges that may be encountered when attempting to do so in different political, legal, and socioeconomic contexts.

Key concepts

Consumption-based water management (CBWM), like so many aspects of water management and policy, is complex. It is also underpinned by a number of key concepts, some of which are defined as follows:

1. **Consumptive water use (or water consumption)** refers to the net portion of water extracted from a water source that is permanently removed from that resource and as such cannot be reused. This is water that is evaporated from soil, transpired by, and embodied in, plants. It can be either beneficial or non-beneficial.
    - **Beneficial water consumption** – also known as beneficial evapotranspiration refers to water consumption that has value to the economy, society, and ecosystems, including water crops, woodlands, grasslands and natural landscapes.
    - **Non-beneficial water consumption** – also known as non-beneficial evapotranspiration refers to water consumption that occurs on unproductive lands, such as saline–alkali areas and deserts, and from open reservoirs. At field scale, unproductive consumptive losses occur as evaporation from bare soil and wetted soil and crop surfaces that are not used by the plant and therefore do not contribute to production.

2. **Non-consumptive water use** is water that remains in liquid status. It comprises either recoverable flows or non-recoverable flows.
    - **Recoverable flows** – also known as recoverable return flows – are flows that return to a river or aquifer for potential reuse.
    - **Non-recoverable flows** – also known as non-recoverable return flows – are flows that return to the sea or another economically unviable sink, such as a saline aquifer.
3. **Water extractions** – also referred to as abstractions, diversions or withdrawals – refers to the gross volume of water extracted from a water source. Most water licensing regimes allocate water on the basis of gross extractions rather than net consumption.

Further information on these concepts can be found in Batchelor *et al.* (2016); Wada *et al.* (2010); and World Bank (2013).

1.3 Issues with irrigation efficiency

CBWM has been developed as a way to better account for water use, recognizing that irrigation efficiency upgrades, perversely, may increase the volume of water that is diverted and consumed at a basin-scale (World Bank, 2013). It is therefore necessary to briefly examine the irrigation efficiency paradox (Grafton *et al.*, 2018).

Modernizing irrigation infrastructure to make it more efficient (by switching from flood to drip irrigation, for example) has long been suggested as a means of saving water and reallocating those savings to other uses, including the environment. However, a significant body of literature, including a report for FAO (Perry and Steduto, 2017), has made it abundantly clear that in most instances, such upgrades result in more, not less, water being consumed at the basin scale. Briefly, the mechanics are as follows. First, improved irrigation efficiency increases net water availability (by using less water to generate the same crop yield). This typically results in the unused portion being reused by the farmer to support additional crop production. This occurs through local expansion of cropped area (where possible), switching to more valuable crops which require more water, or some other form of intensification. The end result is increased net consumption of water, as opposed to the hoped-for savings (Batchelor *et al.*, 2014 and Batchelor *et al.*, 2016). Second, increased efficiency can in certain instances reduce the volume of water that is lost to aquifers and connected surface water resources (recoverable return flows) (Batchelor *et al.*, 2016). This in turn diminishes the flows available for downstream consumptive uses and the environment.

It is important to note that the right governance arrangements can prevent irrigation efficiency upgrades from resulting in basin-wide increases in water consumption (Batchelor *et al.*, 2016; Wheeler *et al.*, 2020). The elements are as follows: basin-wide limits on consumption; water rights which consider water extractions, water consumption and return flows; individual water allocations controlled by licenses or quotas; accurate measurement of water extractions; accurate water accounting; and strict compliance and enforcement at the basin and individual scales. In practice, this combination of elements is rarely present. (See **Chapter 3** for a detailed discussion of this topic).

1.4 Consumption-based water management – the fundamentals

Consumption based water management (CBWM) can be used to address overextraction in irrigation-dependent basins. It does this by reducing non-beneficial ET, which in turn may generate genuine water savings if combined with the right technical, legal, and broader governance settings. These settings are discussed in considerable detail in **Chapter 3** and **Chapter 4**. However, for the purposes of this introductory chapter, the fundamentals of these settings are as follows.

First, for water savings to occur, the specific ET (or consumptive) requirements for crop production must be determined and water strictly allocated on that consumptive (net) basis (with provision for unavoidable conveyance loss). Second, water rights must be defined in terms of water extraction, consumption and return flows. When combined with appropriate monitoring and enforcement this allows for greater control over these elements of the water cycle and in turn greater certainty vis à vis water conservation. Third, ET and land cover monitoring is used at a relevant scale to track land use changes so that allocations may be adjusted to ensure water consumption remains within specified limits. Fourth, target ET allocation is compared with actual ET to determine the basin water balance, with subsequent adjustments to water allocations to again ensure that consumption remains within specified limits (World Bank, 2013).

It is important to note that for CBWM to meaningfully contribute to improvements in the health of over extracted water resources and associated ecosystems, it must be integrated into a broader framework which considers, amongst other things, the environmental flows (defined as the quantity, quality and timing of water) required to sustain these systems and the human beings that depend on them (Linstead, 2018; Horne *et al.*, 2018; International River Foundation, 2007). This is discussed in greater detail in **Chapter 2** and **Chapter 3**.

1.5 Water scarcity in Asia – now

Overextraction of water resources and the subsequent need to generate genuine water savings and to reallocate these savings to other uses, in particular the environment, only arises when demand outstrips supply. It is therefore important to provide a brief overview of the current state of play regarding water availability and security for a variety of uses across the Asia–Pacific region.

In its 2020 Global risks report, the World Economic Forum listed water crises in its top ten risks in terms of likelihood and top five risks in terms of impact (WEF, 2020). These risks are amplified in the Asia–Pacific region, which is currently home to 4.5 billion people and accounts for approximately 65 percent of water withdrawals globally. Eighty percent of these withdrawals are for irrigated agriculture (Asian Development Bank, 2016), which in many parts of the region has resulted in extraction levels exceeding renewable freshwater resources, making them dangerously unsustainable from an ecological, social, and economic perspective (Satoh *et al.*, 2017). Approximately 30 percent (1.2 billion people) of the region's population, are currently exposed to water stress (Wada *et al.*, 2010), which occurs when demand for water exceeds its availability (either because of insufficient quantity or quality, or both) (European Environment Agency, 2021).

Against this backdrop, it is perhaps unsurprising that a significant number of the 47 transboundary river basins that are situated partially or entirely within Asia have been classified under the Global Environment Fund's Transboundary Waters Assessment Programme (GEF TWAP) as high risk across a number of indicators, notably environmental water stress, human water stress, wastewater pollution and exposure to drought and flood (GEF TWAP, undated). This includes river basins such as the Indus, the Ganges– Brahmaputra–Meghna and the Mekong, which not only traverse geopolitically sensitive zones, but together support a significant percentage of the world's population (approximately 800 million and growing) (GEF TWAP, undated).

Agriculture remains the largest water user in Asia, with practices such as irrigating during the dry season exacerbating water scarcity (Asian Development Bank, 2016). Groundwater resources are in a particularly imperiled state, with irrigated agriculture having driven the overexploitation of aquifers across large parts of the region. Seven of the fifteen highest abstracters of groundwater in the world are located in the Asia–Pacific region (Asian Development Bank, 2016), whereas three out of the four most depleted groundwater resources globally are located in China, India and Pakistan (Wada *et al.*, 2010). This includes aquifers in two of the region's major food baskets, namely the north China plain and northwest India (UNECSO, 2020; Jia, 2011). This is particularly concerning given the vast populations supported by these river basins, to say nothing of the quantity of food grown for export to other parts of Asia and the world (Statista, 2011).

The links between water security and food security are well established. Asia contains 70 percent of the world's irrigated area, and 34 percent of the cultivated land in the region is irrigated (as opposed to 10 percent in the United States of America and 10 percent in Africa). As a consequence, water security is food security (Mukherji and Facon, 2009). Water scarcity, combined with poor policies and practices across a range of spheres, can therefore lead to moderate or severe food insecurity in the region (as per SDG Indicator 2.1.2) and further entrench nutritional disadvantage amongst vulnerable groups (UNDESA, 2014).

According to FAO, although undernourishment has decreased across Asia over the last decade, it is on the rise in Western Asia. Further, the prevalence of undernourishment in South Asia is 15 percent, making it the highest in the region (FAO, IFAD, UNICEF, WFP & WHO, 2019).

There is growing recognition that water and food security must be considered within the context of demand for energy (this being known as the water–food–energy nexus) (Taniguchi *et al.*, 2017). In the first instance, water is a necessary input to energy; that is, it is required to extract raw materials such as coal and gas and to generate electricity. In this sense, and as noted above, it competes with the agricultural sector for water. However, energy is also a necessary component of many agricultural practices. For example, South Asia uses USD 3.75 billion worth of energy per year to pump approximately 210 km3 of water, mostly for irrigation. Furthermore, groundwater irrigation uses 15 percent to 20 percent of electricity in India (Barker and Molle, 2004), with this demand having been driven by agricultural electricity subsidies resulting in a cumulative power utility debt of USD 67 billion by 2015 (Sidhu *et al.*, 2019). It is argued that these subsidies have in turn created a powerful incentive to extract more groundwater, thereby contributing to high depletion rates (Badiani-Magnusson and Jessoe, 2019).

1.6 Water security in Asia – 2020 to 2050

Without intervention, ongoing overextraction of water, in particular groundwater, will be exacerbated by population growth, changing dietary preferences and increasing demand across different sectors (Asian Development Bank, 2016). Specifically, water demand for irrigation, domestic use and industry is predicted to increase by 30 percent to 40 percent by 2050 (Satoh *et al.*, 2017), thereby illustrating “growing and acute competition among principal water users” (Asian Development Bank, 2016, p. 40). According to the Organisation for Economic Co-operation and Development (OECD), global energy consumption will double between now and 2050, with non-OECD Asia (which includes China and India) accounting for the majority of this increase in use (IEA, 2019). As noted above, energy and water are inextricably linked, once again highlighting the need for intersectoral dialogue and policy, and due consideration of how competing demands will be managed.

This is vital when considering population growth and water stress. Specifically, it is predicted that the region’s population will reach approximately five billion by 2050. Modelled projections suggest that of these, 1.6 billion to 2 billion will experience severe water stress conditions by the middle of the century (Satoh *et al.*, 2017), whereas Afghanistan, the People’s Republic of China, India, Pakistan and Singapore will have the lowest per capita water availability (Asian Development Bank, 2016). It is also expected that in the decade beginning 2050, seasonal water stress will intensify and areas experiencing severe water stress will expand, with this being primarily driven by demand (Satoh *et al.*, 2017). This increase in demand will have a significant impact on already-depleted groundwater resources in the region, with the World Bank estimating that by 2032, 60 percent of the aquifers in India will be in a “critical state” if current trends continue (World Bank, 2010).

This is particularly concerning as approximately 60 percent of irrigated agriculture and 85 percent of drinking water in the country depends on groundwater extractions.

Although water scarcity in Asia is expected to be primarily driven by socioeconomic changes, rather than climate change, the latter will clearly intensify demand-related shortages (Satoh *et al.*, 2017). We refer to this as the “overextraction–climate change nexus” (see Box 1). Literature examining this nexus in the Asian context is sparse, possibly because of a dearth of data. By way of contrast, the more generalized impacts of climate change on the hydrological cycle are widely reported and include “changes in precipitation patterns and increases in the intensity and frequency of extreme events; reduced snow cover and widespread melting of ice; rising sea levels; and changes in soil moisture, runoff and groundwater recharge.” (World Bank, 2010, p. ix). Within this broader context, recent commentary by the United Nations reinforces Asia’s particular vulnerability to water and climate-related crises and extreme events including flooding and prolonged drought. Unsurprisingly, groundwater is particularly vulnerable to this interplay, with increasing surface water scarcity augmenting demand for already overexploited aquifers (UNESCO, 2020). Climate change is discussed in more detail in Chapter 3 of this report.

The overextraction–climate change nexus will continue to marginalize the most disadvantaged members of Asian society including women, Indigenous Peoples, and small landholders (UNESCO, 2020). Indeed, the links between water and human and environmental well-being are well established and are now inscribed in the Sustainable Development Goals (SDGs) which were adopted by the United Nations General Assembly in 2015 (UNGA, 2015). The following year, these links were explicitly acknowledged by the Asian Development Bank in relation to the region, with the Bank noting that there “needs to be a more concerted effort to incorporate water into climate policy and to reinforce the links between improved water security, sustainable development, and poverty reduction.” (Asian Development Bank, 2016, p. 10).

Box 1. What is the overextraction–climate change nexus?

There is no single definition of overextraction of water resources (also known as overuse), in part because there is no single definition of what constitutes a sustainable level of extraction.

However, it is increasingly recognized that any conception of overextraction must consider the extent to which extraction compromises the health of a river system, floodplain, or aquifer and in turn its ability to maintain water security for a variety of users and uses into the future, including cultural and spiritual uses and as a habitat for water-dependent species.

In this sense, overextraction considers the environmental flows required to maintain ecosystem function (noting that assessing ecosystem function and determining which elements are essential and must be preserved or restored is also a complex exercise). For groundwater, this requires consideration of the balance between extraction and the rate at which the aquifer in question is recharged, and the consequences of declining water tables, such as saline intrusion in delta aquifers.

It is widely recognized that many water resources across Asia – in particular groundwater resources – are already subject to overextraction. Thus, the starting point for many rivers and aquifers is an unsustainable level of extraction based on historical climatic norms (Wada *et al.*, 2010).

However, the climate is changing and as a consequence water scarcity is increasing in certain regions (see **Chapter 3** for further details). This means that the impacts of historical and ongoing overextraction are being exacerbated by climate change. This dual challenge forms the basis of the term "overextraction–climate change nexus".

Significantly, the overextraction–climate change nexus threatens to undermine the health and resilience of freshwater ecosystems across Asia and in turn the achievement of certain SDGs, in particular SDG 1 (No Poverty), SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation). CBWM is a potential tool to reduce extraction in irrigation-dependent basins and accordingly to contribute to the realization of these and other SDGs (Asian Development Bank, 2016).

References

Asian Development Bank. 2016. Asian water development outlook 2016: strengthening water security in Asia and the Pacific. Philippines.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., & Bierkens, M.F.P. 2010. Global depletion of groundwater resources. Geophysical Research Letters. 37(20).

Chapter 2. What is consumption-based water management and where might we need it?

Consumptive water use is defined by the United States Geological Survey as “water that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not available for immediate use” (Maupin, Ivahnenko and Bruce, 2018, p.56). The main portion of consumption is evapotranspiration (ET), which is the process by which liquid water is converted to atmospheric water vapour by evaporation from land and water surfaces and by transpiration from vegetation as part of plant photosynthesis and growth. Notably, when water diverted from a lake or a river is consumed, it is no longer available to other users downstream.

Consumptive uses include: all rainfed and irrigated cropping; forestry; bare water evaporation from lakes and other waterbodies; and ET from bare soils and all other forms of vegetation. Non-consumptive uses are conventionally considered to include hydropower, recreational use and domestic water supply and sanitation, where the return flows are treated to a standard fit for reuse. In practice, a portion of water supplied for domestic consumption and sanitation is used consumptively (in gardens, parks and so on) and may be too degraded for safe reuse in many parts of Asia.

To understand where and why managing consumptive use is desirable, it is useful to revisit some basic concepts in hydrology and water resources management. As such, this chapter outlines the fundamentals of water development for human use and the hydrologic cycle, as well as the components of the water accounting and allocation system that must be in place before CBWM can be adopted. It also reviews the concepts of real and apparent water savings (and the associated paradox of irrigation efficiency) and explains the role of ET monitoring in managing and constraining agricultural water consumption.

2.1 Water use and water availability

Water is a fugitive resource in that it seeps and flows across the landscape and can transform from one state to another – solid snow and ice, liquid water, and gaseous water vapour. Since the earliest days of human development, water has been abstracted and captured for settlements, drinking, and washing, power production, other industrial processes and agriculture.

2.1.1 Trajectories of water development

A typical trajectory of water development within a river basin is shown in Figure 1. The natural unit for water resources management is a river basin or catchment (GWP, 2000), although humans living within them have historically only had interest in water resources close at hand in rivers, streams and lakes as well as from groundwater via springs andshallow wells. A significant part of historical water development occurred as a result of riparian settlements seeking reliable sources to satisfy their various needs.

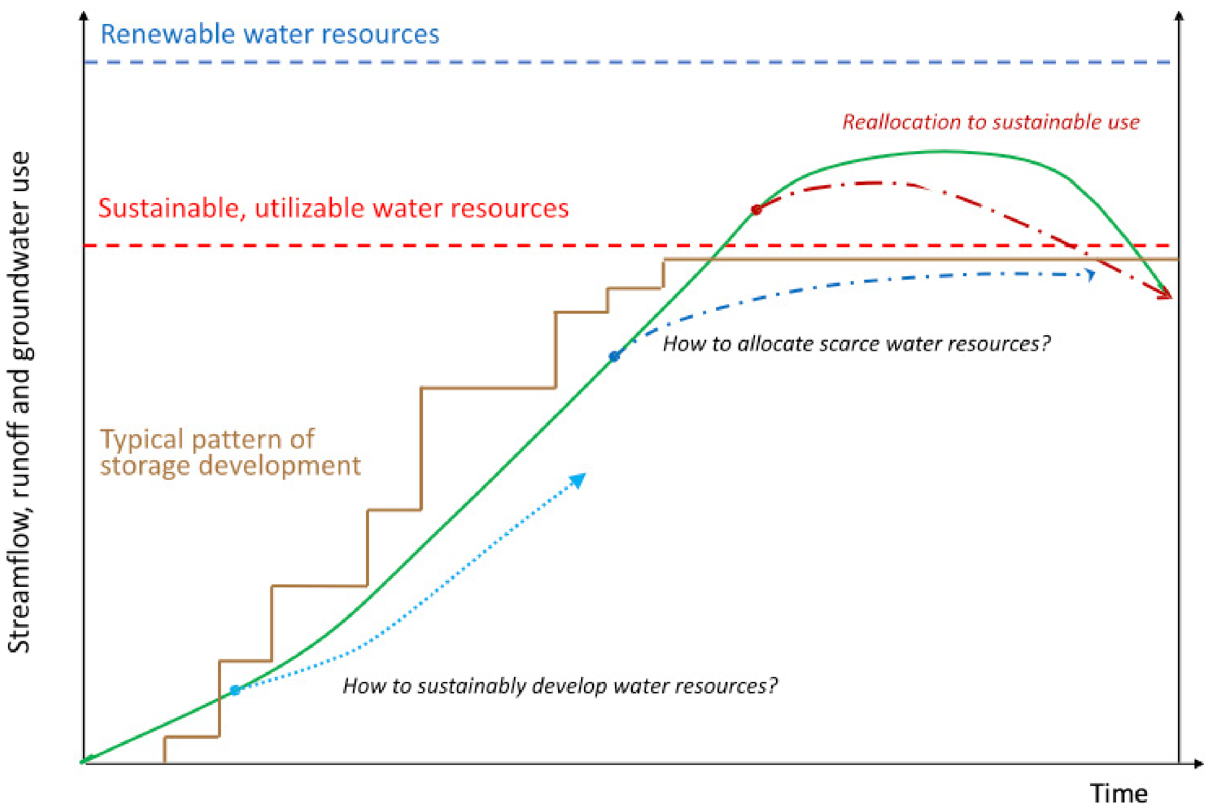


Figure 1 Evolution of water development in a river basin

Source: Adapted from Molle, Francois & Mollinga, Peter & Wester, Philippus. (2009). Hydraulic Bureaucracies and the Hydraulic Mission: Flows of Water, Flows of Power. Water Alternatives. 2. 328-349.

The volume of **renewable water resources** (rainfall, runoff and groundwater recharge) exceeds the **utilizable** volume for a number of good reasons, including limited accessibility to water in snow and ice in mountainous regions, flood events and deep groundwater storage. The historical concept of utilizable volume is imprecise and fluid, ranging from allowing or even encouraging full use of water for human consumption to recognizing the importance of in-stream flows and safeguarding outflows to the sea that support coastal and marine environments.

As water use approaches the utilizable limit, however well or poorly defined, there is increasing awareness of limitations in water supply to meet all demands, all of the time. This can encourage both better **accounting** of water availability and use, and better allocation of water between competing demands. Once the utilizable limit is exceeded, water use must be constrained, and **reallocation** of supplies is required for long-term sustainable use. A **cap** on water use may be implemented at or below the utilizable limit and a cap may be set in advance of reaching a defined limit if sufficient information and awareness exist. Clearly, reallocation after exceeding the utilizable limit is more difficult, painful, disruptive and expensive than setting a cap on water use at an earlier stage. In some countries, the imposition of a cap on water resources allows the development of water trading to facilitate reallocation and increase the economic value of water use. However, the development of successful water markets requires many processes to be well established, including good water accounting, effective and appropriate water rights systems, functional water allocation processes, strict compliance and enforcement mechanisms, and users' acceptance and motivation to trade.

Sustainable water use at the basin scale can be defined in terms of a sustainable diversion limit (SDL), which is set to maintain healthy and effective aquatic ecosystems. An SDL is a specific type of cap that is clearly defined by an assessment of a desired ecological state in a river basin and an accompanying set of environmental water allocations, based on best available science (MDBA, 2019).

A key factor in the emergence of water scarcity is variability in water resources availability from year to year and sometimes from season to season (FAO, 2008). Supply-side solutions to both forms of variability have been to develop surface water storage in dams and reservoirs (the stepped region of the development trajectory in **Figure 1** and to increase the utilization of groundwater, which can be thought of as a natural form of interannual water storage. In the early stages of water development there has generally been little consideration of interannual variability except perhaps in arid and semi-arid countries such as Australia and the western United States of America, where average availability means little. From the middle of the twentieth century, many irrigation **entitlements** in Australia's Murray–Darling Basin were specified in relation to long-term mean water availability calculated for a system, with the actual **allocation** being adjusted every year on the basis of water available in storage, and likely inflows with a given probability (one in one hundred years), based on the historical climate record. In the western United States of America, interannual variability under the prior appropriation doctrine is addressed through the concept of seniority, where older rights must be satisfied before junior ones in times of shortage.

The importance of maintaining in-stream and end-of-river flows and providing sufficient water to maintain natural (mostly aquatic) ecosystems is belatedly being realized across the world. Major reallocation of water for environmental use is taking place in Australia's Murray–Darling Basin (MDBA, 2010) and further adjustments are likely as better understanding and valuation of environmental water needs emerge, and the complicating effects of climate change are included.

Few countries in Asia have formal environmental water allocations, evidenced by increasing frequency of years when a river no longer reaches the sea, for example the Indus in Pakistan and the Yellow River in China (Young *et al.*, 2019; Yang *et al.*, 2004). Setting an appropriate level of environmental water allocation is constrained by limited understanding of the water balance (i.e., who is using water and where), the politics of existing interests, and knowledge about the costs of environmental degradation and the benefits of environmental water allocation. Australia is aiming for an average environmental flow allocation of about 60 percent of mean annual flow from a recent level of about 40 percent in the Murray– Darling Basin and more in most catchments around Australia, whereas current specifications in the Yellow River in China are between 15 percent and 20 percent and are focused on maintaining adequate flows for sediment transport. Minimum end of system flows for the Indus have been suggested at only 3 percent of mean annual flow (MAF) with 21 percent of MAF for the Indus Delta and a floating allowance for much larger flow events over a five- year window (Gonzalez, Basson and Schultz, 2005; Young *et al.*, 2019).

When a river basin is fully allocated (at the utilizable limit, or some better-defined limit of sustainable water use), it is said to be closed (Molden, 1997), with consequences that are explored later in this chapter. Since irrigation is the dominant consumptive use of water, it plays a central role in all efforts to conserve and re-allocate water and provides the principal source for restoration of environmental water needs.

Figure 1 describes a typical trajectory for the development of water resources in the form of stream flow and groundwater, which are the sources that are managed and manageable. In practice, the hydrology of catchments also affects the availability of utilizable water resources as changing land use may change the consumption of rainfall and the generation of runoff and stream flow and, in some circumstances, the recharge of groundwater. Thus, in the bigger picture of water resources assessment and development it is important to understand the hydrology and water use of forests, pastures and rainfed agricultural lands. Landscape management can make long-term changes to the water balance and patterns of water availability in a river basin, which typically need evaluation on a case-by-case basis (Calder *et al.*, 2007). For example, extensive upstream watershed development for agriculture may reduce runoff and groundwater recharge that was previously available downstream.

At this point, it is useful to briefly consider the hydrologic cycle and its associated water balance to consider its implications for managing consumptive water use.

2.1.2 The water cycle

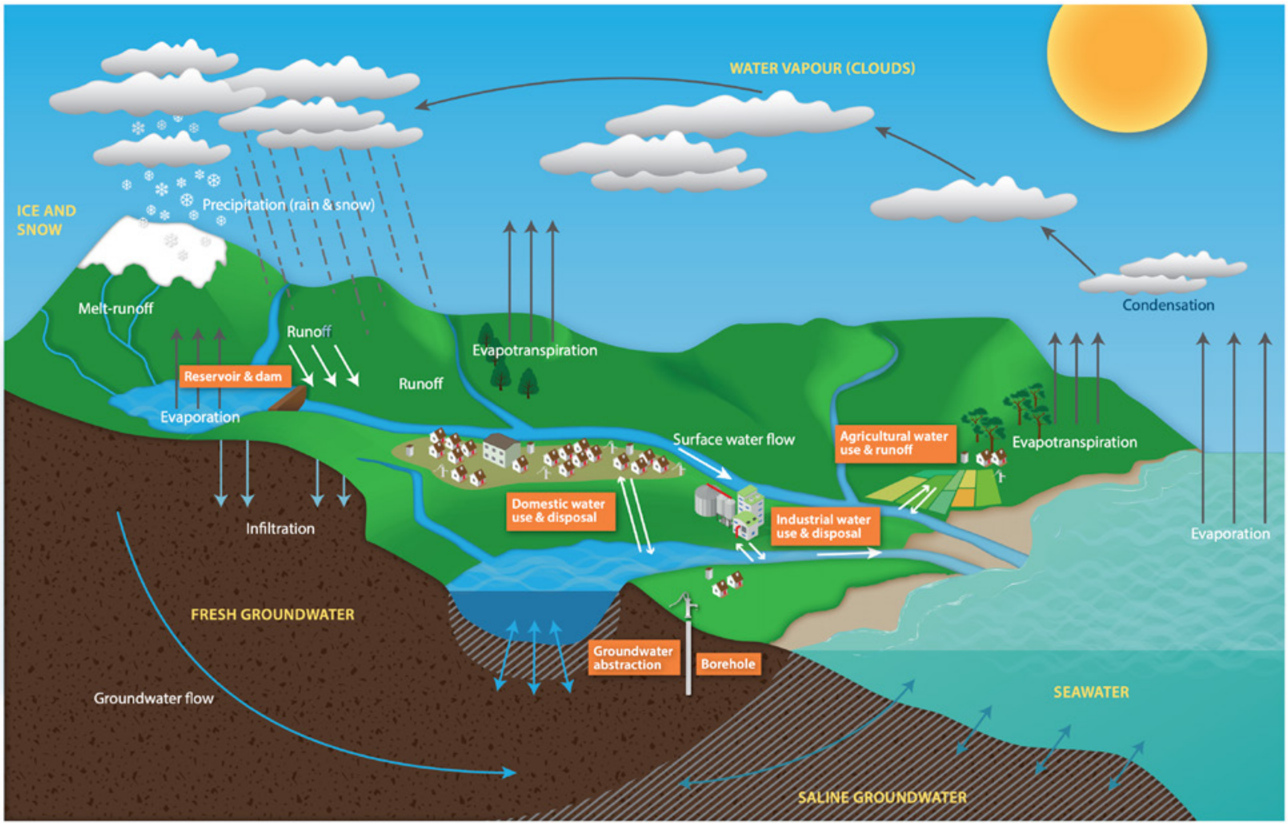


Figure 2 Conceptual water budget for a river basin

Source: Nowicki, S., Gladstone, N., Katuva, J., Greeff, H., Manandhar, A., Wekesa, G., & Mwania, G. (2018). Simple diagram of the water cycle. The Water Module- Student Resource, School of Geography and the Environment, University of Oxford.

The principal components of catchment hydrology are shown visually in Figure 2 and in the annual water balance equation (Equation 2-1) below. The input of the water balance is precipitation, including snow and rain. The second largest component of the water balance is evapotranspiration (ET), consisting of evaporation from soil and water surfaces and transpiration from all forms of vegetation which, combined with evaporation from the sea, generates rainfall and gives rise to the term "hydrologic cycle". The third largest component of the water balance is surface runoff, as streamflow, which may be stored in lakes and dams and may subsequently recharge groundwater through various pathways.

The change in storage under long-term natural conditions approaches zero, but with human intervention, there can be significant changes especially when groundwater abstraction exceeds recharge.

$$P = ET + RO + \Delta W_{gw+sw} \quad (2\text{-}1)$$

where:

ET = evapotranspiration, $m^3\ y^{-1}$ P = precipitation, $m^3\ y^{-1}$

RO = catchment or basin runoff, $m^3\ y^{-1}$

ΔW_{gw+sw} = the change groundwater and surface water storage, $m^3\ y^{-1}$

Annually, the volumes of each water balance component may be in the order of millions and billions of cubic metres.

Until recently, ET over a landscape could not be measured directly and was either assessed by measuring the other components of the annual water balance or by interpolation of point-based measures, the simplest of which is an evaporation pan. It can also be estimated from hydrological models that incorporate land use and soils information.

Estimating a large component of a water balance from known smaller ones (runoff and change in storage), especially if they are not well measured, is inherently prone to error and is therefore uncertain. The advent of direct measurements of ET by energy balance, calculated from remote sensing data, facilitates the potential for active management of consumptive use (Chapter 4, Chapter 1, Chapter 2 and Annex 1) and allows better attribution of errors within the water balance.

Figure 2 illustrates multiple variants and pathways for each of the water balance components: 1) runoff from snow melt and from different parts of the landscape; 2) ET from irrigated land (abstracted surface and groundwater), rainfed cropland, forested land and other land cover; 3) bare water evaporation from lakes, dams, streams and wetlands; and 4) groundwater recharge and discharge at different points in the landscape that are both natural and result from pumping. Both rainfall and ET can be highly variable over space and time and the flow pathways between different parts of the catchment, and therefore between different uses and users, are complex and often hard to map and define.

Catchment hydrology in arid conditions has different characteristics from those in the humid tropics and temperate regions. In arid and semi-arid conditions, such as found in Afghanistan, Australia, many parts of India, Islamic Republic of Iran, and Pakistan, actual ET is almost as large as precipitation. Runoff is typically a small percentage of annual precipitation, even below 5 percent in continental Australia (McMahon *et al.*, 1987).

Furthermore, groundwater recharge may be a small percentage of surface runoff – the residual of a residual – and groundwater recharge may be very slow or dominated by episodic flooding events, which recharge shallower aquifers as well as deeper ones.

In contrast, ET will be a much lower proportion of precipitation in the humid tropics and temperate climates, where the energy to drive ET is limited by extensive cloud cover (tropics) and low temperatures (temperate) (Budyko, 1948). Consequently, runoff and groundwater recharge are much larger proportions of an annual water balance.

Available water resources can be significantly reduced by pollution from point sources such as industrial return flows and untreated urban and rural wastewater (Damania *et al.*, 2019). Non-point source pollution from agriculture (nitrate fertilizer, pesticides, salinity, livestock effluents, antibiotics) increase water treatment costs for potable supply and may preclude agricultural use. Water quality is playing an increasingly important role in water scarcity in Asia (ESCAP, 2020) and wastewater is also considered to be an underutilized resource (WWAP, 2018).

Irrigation is the dominant water use in Asia and elsewhere. Estimated national and river basin water use by different sectors and tabulation of renewable and utilizable water resources can be found from multiple sources including Shiklomanov and Rodda (2004), Shiklomanov (2000), FAO (2021a), WWAP (2012) and Piesse (2020).

Throughout Asia, irrigation typically accounts for about 90 percent of diverted water resources. In Pakistan, it accounts for 70 percent of available water resource use (FAO, 2021a) in the Indus River Basin.

Total water use in the Hai River Basin (China) exceeds annual average available basin water resources (118.6 percent in 2015) because of the year-on-year groundwater overdraft (IWHR, 2019). Unusually, in the Hai River Basin, and across northern China, the proportion of irrigation water use to total abstraction has fallen from over 90 percent in the 1980s to less than 63 percent at present (National Bureau of Statistics of China, 2019). Demand from urban centres and industry now accounts for more than 30 percent of use and is expected to exceed 40 percent by 2050. In southern China, irrigation water use is much smaller in absolute terms and as a fraction of abstraction. In countries as large as China, statistics shaped in terms of national water use are therefore not very useful compared to regional and basin level disaggregation.

In the Colorado River in the United States of America, the highest withdrawals in both upper and lower halves of the basin are for hydropower generation, whereas the consumptive use is dominated by agricultural use and cooling for thermal power plants runs a close second (Maupin, Ivahnenko and Bruce, 2018).

The availability and use of water resources is further complicated by climate change (FAO, 2008; Batchelor *et al.*, 2016; Taylor *et al.*, 2013). Broadly speaking, areas that have low rainfall and high temperatures are expected to experience further declines in rainfall and higher temperatures. In Pakistan, higher temperatures are expected to increase crop water demand, crop productivity and soil moisture deficits, although long-term projections for water availability are more or less stable (Young *et al.*, 2019). Temperature-induced increase in vapour pressure deficit has become a more important driver of ET in Australia since 1990 and the influence of windspeed as a driver of evaporation declined from 1975 to the middle of the 1990s (Stephens *et al.*, 2018).

Enrichment of atmospheric CO_2 is correlated to an increase in global greening (Donohue *et al.*, 2013), and greening across arid Australia has been implicated in reduced stream flows (Trancoso *et al.*, 2017). Although the Penman–Monteith equation has been updated to incorporate the effects of temporal changes in CO_2, most global climate models (GCMs) are not able to simulate increased water use because of greening and higher CO_2 concentrations and therefore have predicted increases in runoff where decreases have actually been observed (Yang *et al.*, 2019). Overall, the implications for irrigated agriculture in arid and semi-arid Asia are that water resources availability will be static or in decline, with increased crop water demand for a given level of production and slower and lower rates of groundwater recharge.

Monsoonal areas in Asia are expected to experience increased average rainfall, but with a greater proportion of high intensity events, coupled to more frequent and longer dry periods between them (Turral, Faures and Burke, 2011; Batchelor *et al.*, 2016). The precise impacts of climate change on water resources in Asia are inferred by global climate modelling at a coarse scale, and from calibrated downscaled regional climate models (RCMs), to better incorporate local climate patterns, topography, vegetation and land cover effects. Ensembles of GCMs are increasingly used to force RCMs and derive regional climate scenarios with higher levels of certainty, for example in the CORDEX programme (Georgi, 2019). Water resources assessment under climate change is conducted using catchment- based modelling using scenarios derived from RCMs runs (FAO, 2019).

A significant impediment to the interpretation of modelling and validation is a lack of good quality time series data on stream flows and climate across many parts of Asia, excluding China.

Nevertheless, the analysis of climate change impacts on water resources availability in Asia and on crop and vegetation water use is an important and increasingly active area of research and routine assessment (for a Mekong Basin example see Trisurat *et al.*, 2018).

Factoring the impacts of climate change into future water use and water demand is complex, and the results remain uncertain. However, their importance will only increase, and they will need to be routinely incorporated into water planning and allocation across the region.

2.2 Consumptive use in practice (the old and the new)

The management of water in terms of consumptive use has long been a feature of the water accounting used in the prior appropriation doctrine of water rights in the western United States of America (see Box 2). Since 2010, it has been developed in China as a pilot process in some counties within the Hai River Basin, and more completely in the Turpan Basin in Xinjiang Province. Although water accounting and allocation processes in Australia are highly developed, the country does not consider consumptive use.

The western United States of America

The total water appropriation for the Colorado Basin, which comprises about 16 million acre feet (MAF) is defined in terms of a volume of consumptive use. Under interstate water sharing arrangements laid out in the Colorado River Compact, 1922, the amount of water that upstream rights holders, even senior ones, can consume is limited by the requirement to maintain or exceed specified flows at certain points in the basin, principally the boundary between upper and lower basins (Stern and Sheikh, 2019). The issue of rights in the basin is in part based on a computation of notional return flows arising from diversions, estimated crop patterns, irrigation management practices and irrigation delivery losses through a complex water balance analysis (Wilson Water Group, 2015) with a large number of assumptions and reference ET calculated using the Blaney–Criddle equation (Maupin et al, 2018). Rights in the upper basin are not fully apportioned to their share of 7.5 MAF and high storage capacity in the upper basin (equivalent to four years of mean annual flow) allowed demand in the lower basin to be met through 11 consecutive years of drought at the end of the twentieth century (USDI, 2012).

Box 2. Prior appropriation doctrine of water rights in the western United States of America

Under prior appropriation, water remains the property of the state with usufructuary rights allocated to individuals, businesses and organizations on the basis of "first in time, first in right". That is to say that senior (earlier) rights holders take precedence over newer rights holders in conditions of low flow, such as drought, as a means of sharing water under variable supply conditions between and within years. A right is typically defined by its location, volume of water, date of diversion and specification of a beneficial use.

Beneficial use is an important concept within the doctrine and if no beneficial use is made of a water right, it can be forfeited ("use it or lose it"). The original intention of mandatory beneficial use was to prevent speculation in water holdings by non-users, but it has led to protracted litigation in many states.

Rights are administered by the district engineer and diversion and land licenses are required for non-riparian use. The allocation of rights is dependent on prior claims and new applications may be subject to legal challenges from senior rights holders who feel their water rights may be impinged. Rights may be transferred between holders, by market transaction, subject to legal challenges from other senior rights holders. In practice, market transfer has been sluggish over much of the western United States of America, since many transfer applications take a long time to work their way through the courts (Smith, 2019).

Routine assessment of consumptive use and its impacts have been embedded in the doctrine because of the need to secure senior right holders' entitlements. For example, California has two senior out-of-basin water rights holdings to the American Canal and to the Imperial Valley Irrigation District, that offtake from the Colorado River in the lower basin, with both junior and senior rights held upstream. In the Colorado River, the total volume of accorded rights was initially set as the mean annual flow of the river, implying complete abstraction of available water. Under the doctrine, in-stream flows were not considered to be beneficial (Smith, 2019) although as early as 1925, state appropriation of water rights for environmental protection was enacted in Idaho. By 1998, the twelve states that apply prior appropriation had established a programme of in- stream flows, that initially focused on the protection of fish as a valid beneficial use and has since been broadened to cover other ecosystem uses, flora and fauna, recreational and aesthetic use (Smith, 2019).

Reference

Smith, S.M. 2019. Instream flow rights within the prior appropriation doctrine: insights from Colorado. Natural Resources Journal 59(1): 181–213.

Significant increases in demand in the domestic, industrial and power sectors, increases in evaporative demand and an estimated 9 percent reduction in mean annual streamflow by 2050 because of climate change, continuing drought and gradual increases in environmental allocation are putting ever greater pressure on water resource management (Stern and Sheikh, 2019) and have prompted assessment of evapotranspiration by remote sensing, often referred to as remotely sensed evapotranspiration (RS-ET), to monitor water rights and water use (Maupin *et al.*, 2018 and Castle *et al.*, 2016). However, to date RS-ET is not the standard method for measuring consumptive use in the basin because of continuing concern about accuracy and calibration of the models and a natural conservatism to continue with established and well-understood procedures.

China

China has been a pioneer in the management of consumptive use of water (ET from irrigated agriculture) as one of the means to address demand-induced water scarcity in the northern part of the country, and in particular the north China plain, where rapid urbanization, industrialization and community development of groundwater for agriculture has resulted in surface water scarcity and severe groundwater overdraft.

The approach has been developed through two large and long-term pilot projects with World Bank assistance: in the Hai River Basin (World Bank, 2011b); and in the Turpan region of Xinjiang (World Bank, 2013). The primary targets of both projects have been to control groundwater table decline and minimize groundwater pumping and consequent overdraft (World Bank, 2011b). Interest in controlling ET dates back to Australian Centre for International Agricultural Research (ACIAR)-assisted research projects in the Hai River Basin that began in the late 1980s, which used data derived from remote sensing and GIS to estimate and compare crop water use and productivity across the lower Hai Basin (McVicar *et al.*, 2002). The GEF/World Bank funded projects in the Hai River Basin began in the early twenty-first century and the second phase concluded in 2014. Work has continued since and become more sophisticated and will be referred to many times in this document.

Following this brief consideration of water development trajectories, catchment hydrology and water balance and water rights based on consumptive use, it is useful to look at water accounting and allocation in broader terms to provide a more general context for consumption-based water management.

2.3 Consumptive water uses in a river basin

Rational water resources management requires good planning that accounts for water availability, its variability and current and future water demand. There are multiple pathways of surface and groundwater flows in a river basin, and users are inevitably connected to each other.

The importance of consumptive use lies in its effects on net instream flows (made up of flows remaining in rivers and streams and stocks in groundwater and surface storage) reaching downstream users, and on return flows (via surface or groundwater pathways) from upstream locations where water has been diverted or abstracted. Flow paths and linkages between surface and groundwater are typically hard to define precisely across a river basin but can be more easily conceptualized over an irrigation system. Although direct measurement of return flows is difficult if not impossible at present, they can be estimated by simple water balance and by catchment modelling.

Water policy serves multiple socioeconomic goals and water allocation policy is one of the tools used to attain them. Effective water allocation is based on up to date water accounting and prediction of future water demand and availability.

2.3.1 Accounting for water use, especially consumptive use

A full treatment of water accounting is provided in FAO Water Report 43 (Batchelor *et al.*, 2016) and the context of water scarcity is treated in FAO Water Report 38 (FAO, 2008). The process of water accounting is succinctly described in Figure 3.

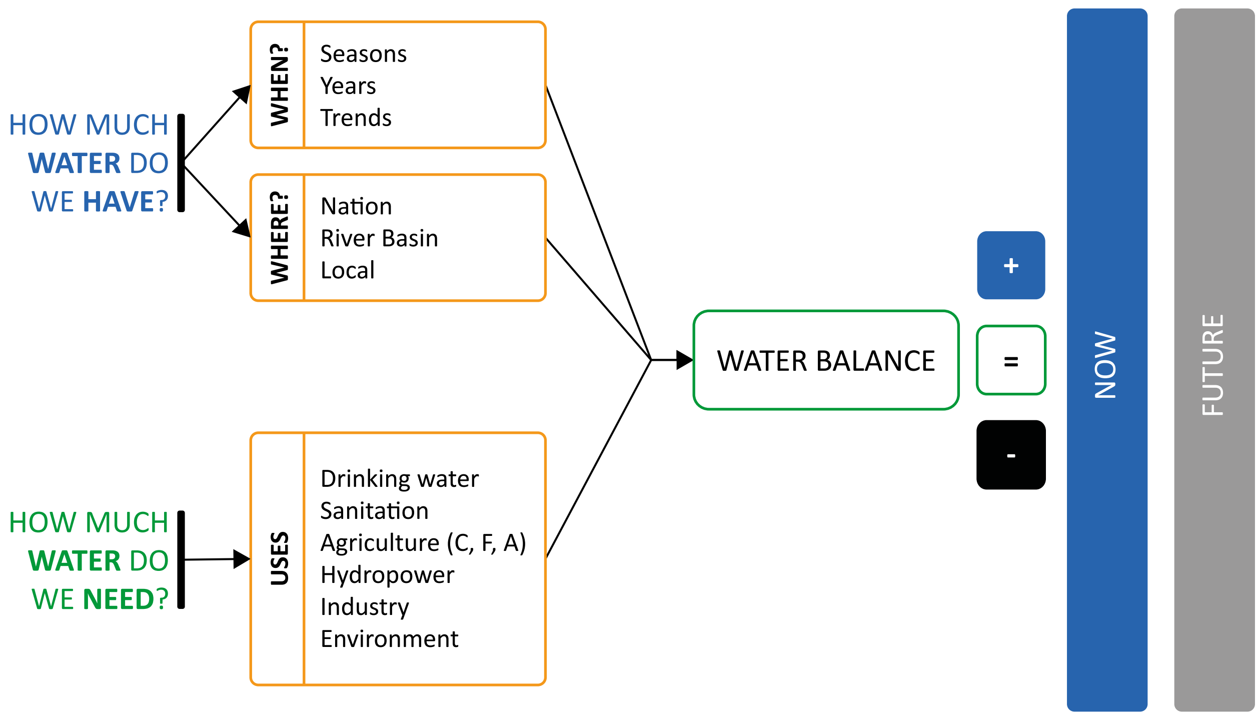


Figure 3 General questions in water accounting

Source: Authors' own elaboration.

At a river basin scale this can be more elaborately described in the “Molden” finger diagram (Molden, 1997; Molden *et al.*, 2003; and Willardson, Allen and Fredriksen, 1994). The novelty of this approach was to consider all components of flow in a river system, with particular focus on depletion of flows by consumptive use (evaporation and transpiration) and by degradation of water quality. Diagrams, such as the one shown in Figure 4, highlight the importance of return flows and surface and groundwater interactions.

The concept of beneficial and non-beneficial depletion distinguishes between water that is used productively (to create food from crops etc.) and water that is lost unproductively from bare soil and bare water evaporation or is lost to a saline sink and cannot therefore be used. **Committed flows** include in-stream and end of system flows that must be ensured for river and coastal health and may include other environmental uses, and non-consumptive flows such as hydropower and a large proportion of domestic drinking and sanitation water supply, that in principle return to the system and contribute to net outflow. **Uncommitted utilizable flows** are those that can be allocated to in-stream, end of system and beneficial depletion in the future.

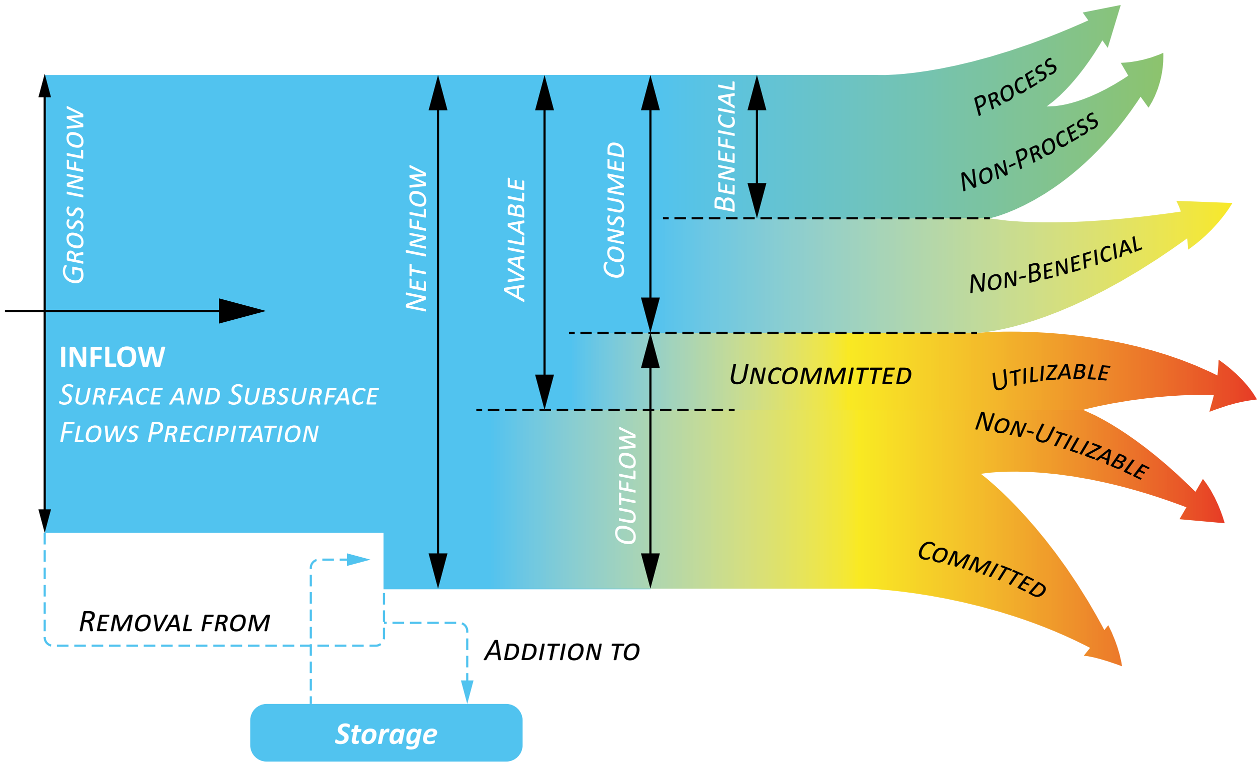


Figure 4 Water balance in a river basin – components of flow

Source: Molden, D., Murray-Rust, H., Sakthivadivel, R. & Makin, I. 2003. A water- productivity framework for understanding and action. In J.W. Kijne, R. Barker, & D. Molden, eds. Water productivity in agriculture: Limits and opportunities for improvement, pp. 1–18. Wallingford, IWMI & CABI Publishing.

These conceptual diagrams do not directly capture seasonal and interannual variability in water availability and use but they can be constructed for average dry and wet conditions and for varying climatic scenarios with climate change impacts. As such they provide a snapshot of a basin water account and are a useful starting point for more detailed analyses using catchment models, time series of hydrologic data and geographically explicit water use.

Since irrigated agriculture is the main consumer of surface and groundwater, a conceptually neater approach has been proposed to investigate water use at field and system scale in order to evaluate potential water savings, the reliance of downstream users on return flows from existing use, and to estimate water productivity and other economically useful indicators (Perry, 2007; Perry, 2012; Perry *et al.*, 2009).

At smaller, well-defined scales, where water is withdrawn for a farm or irrigation system, water use as shown in Figure 5 can be partitioned into beneficial and non-beneficial consumption and utilizable and non-utilizable return flows (**Figure 6**).

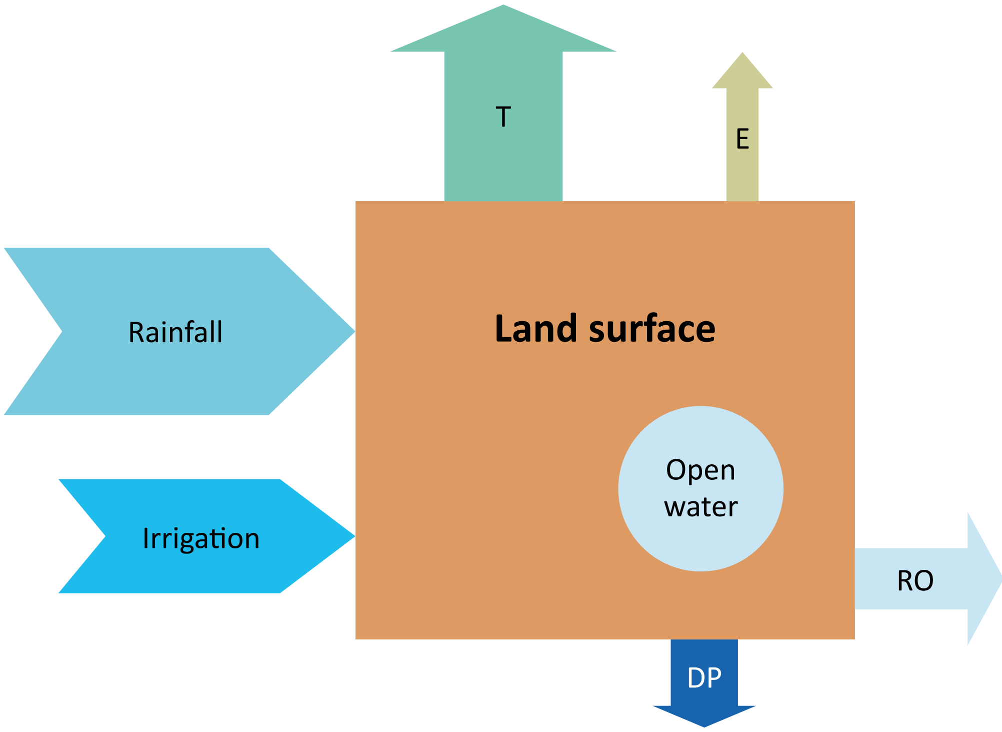


Figure 5 Water balance at field/water course/irrigation system (where irrigation is sourced from either surface or groundwater or both).

Source: Authors' own elaboration.

Where:

RO = Surface runoff (to streams, lakes, wetlands)

DP = Deep percolation (to soil moisture storage and to groundwater)

T = vegetation transpiration

E = bare soil and open water evaporation

In Figure 6, transpiration is beneficial consumption, evaporation is non-beneficial consumption, recoverable return flows are potentially surface runoff and groundwater recharge. Non-recoverable flows may include:

- recharge to a shallow saline water table, which is often present in irrigation systems in arid and semi-arid conditions;
- surface runoff with high levels of pesticides or other contaminants would also be non-recoverable (and hazardous); and
- deep percolation below the crop rootzone might also be non-recoverable if it does not recharge the water table at some point, or if it flows to depressions and is evaporated, or it contributes to waterlogging elsewhere.

There is clearly some grey area in the classification of non-recoverable return flow if it supports natural ecosystem functions, say in wetlands where it is evaporated beneficially but not necessarily in an economic sense.

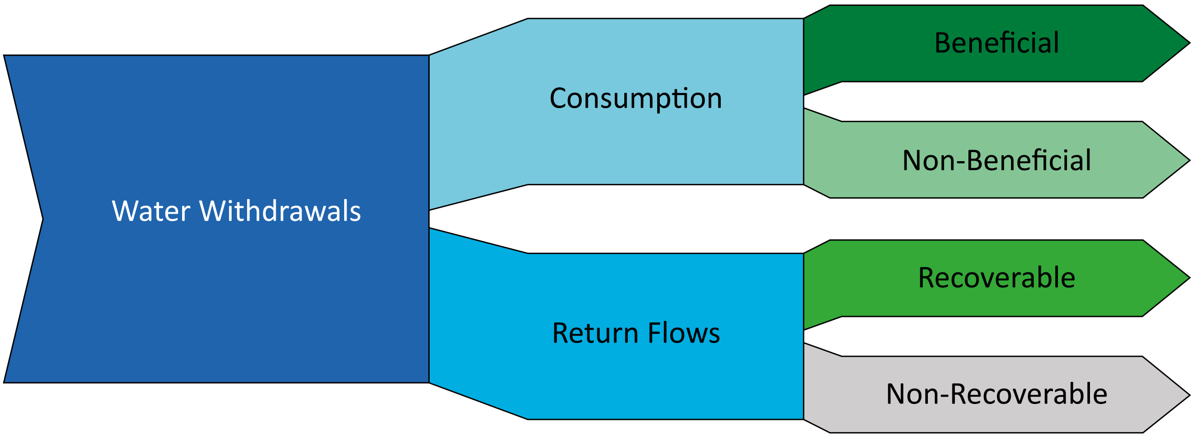


Figure 6 Water balance and the possible outcomes of water abstraction

Source: Pérez Blanco, Carlos & Hrast Essenfelder, Arthur & Perry, C.J.. (2019). Irrigation technology and water conservation: from panaceas to actual solutions.

In experimental conditions, it is possible to determine runoff and deep percolation and measure its quality, although the partitioning of recoverable and non-recoverable components is inferred by context (say, saline or fresh shallow groundwater). In practice it is very difficult to measure recoverable return flows, even when total consumption is measured directly by remote sensing. A first step is to map the most likely pathways, based on hydrological connections, which shows the interdependency of users (Simons, Bastiaanssen and Immerzeel, 2015; Molden, Keller and Sakthivadivel, 2001).

2.3.2 Conserving water: misunderstandings of efficiency and real water savings

When a river basin is fully allocated, further development of irrigated agriculture is not possible. Additionally, reallocation to higher value uses puts further pressure on water availability to farmers. At the same time, as populations grow and become wealthier, the demand for food increases and becomes more varied. In order to maintain food self- sufficiency, more water is needed to grow more food, or more food has to be produced with the same amount or less water (Molden, 2007).

A classic economic response to managing resource-restricted production is to improve the efficiency of production processes and make savings that can be redeployed elsewhere, either in producing the same item or something else. The contrary argument to this is known as the Jevons paradox which, put simply, says that if a benefit is derived from using an input, there is a strong incentive to use more of it to gain more benefit (Perry, 2012; Perry and Steduto, 2017).

In the technical irrigation literature and in practice there has been much effort expended on the efficiency of water use for irrigation, where efficiency is described as the amount of water transpired by a crop divided by the total supply from a diversion point. This incorporates efficiencies and losses during water conveyance in canals and pipes and losses at field level during application (see Figure 5, earlier). There are good reasons to be interested in technical irrigation efficiency in terms of: 1) actually delivering a useful supply to a user; 2) maximizing production from water delivered at a field; and 3) minimizing externalities such as waterlogging, water table rise and salinization. However, the potential for real water savings from efficiency improvements continues to be misunderstood and is well summarized by Perry and Steduto (2017).

Improved irrigation efficiency measures may reduce losses in transmission and field application, but it is the fate of those losses that is important. This has long been understood in some contexts, such as the requirement for minimum flows in the Colorado River to meet downstream needs in the lower basin, where return flows from upstream diversions are explicitly factored in to meeting the minimum requirements (USDI, 2012). In general, the fate of return flows, and their usability has not been tracked or considered in the anticipated water savings made from efficiency improvements, which have been widely promoted by lending agencies and in bilateral aid programmes.

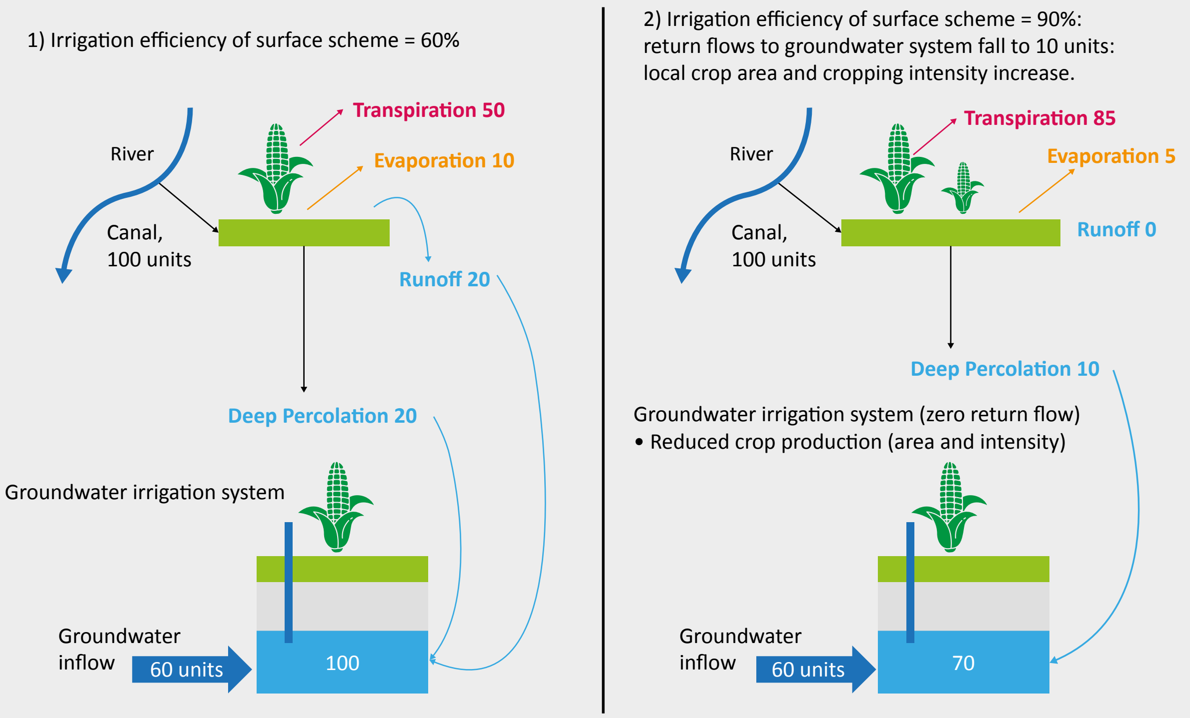
A number of significant points arise from understanding the hydrology, paths, interconnections and flows and uses of water in a river basin:

- If water is already fully allocated in a basin, then the efficiency of use at the basin's scale is consequently 100 percent, or greater if groundwater is being mined, as in the north China plain (130 percent). There can be no net gain in water use and any increase in consumptive use in one part of the basin will reduce water availability in another.
- If efficiency is increased at a site, more consumable water is available to a local user. Unless supply is restricted (by quota or respecification of water right), there is a strong incentive and a documented tendency (Birkenholtz, 2017) for farmers to consume this conserved water to increase production and income, with a consequent reduction in return flows that were being used by others (see **Box 3**).
- Any reduction in **non-recoverable flows** should result in real water savings. Many irrigation systems, especially those in arid and semi-arid conditions, have significant areas that overlie shallow, saline groundwater. Technical efficiency improvements that reduce deep percolation and recharge of a shallow saline water table reduce externalities (loss of production, land and potable water supplies) and potentially generate real water savings if individual and bulk water allocations are reduced.
- Direct measurement of consumptive use provides the proof of the effectiveness of improved efficiency in making real water savings. There are many documented cases where the introduction of high efficiency water saving technologies, such as drip irrigation, has resulted in greater water use (Perry and Steduto, 2017; van Opstal *et al.*, 2021). Similarly, improving agriculture in upstream catchments through upper catchment development and improvement has been shown to reduce downstream water availability, for example in watershed improvement programmes in India (Batchelor et al, 2014; Calder *et al.*, 2007).
- If the intention of introducing water conserving practices is to save water for reallocation elsewhere, then it is important to understand the fate of return flows and establish who is currently using them. There are technologies and contexts where water conserving technologies and agricultural practices can make real water savings (Kaune *et al.*, 2020b), but such interventions will often require associated reductions in water delivery, where the efficiency gains are made.

An integrated basin-scale analysis of water conservation policies in the Upper Rio Grande, United States of America, showed that water conservation subsidies and investments resulted in a net increase in water use by adopters and reduced return flows and aquifer recharge (Ward and Pulido-Velazquez, 2008). The authors noted that the achievement of real water savings requires the design of institutional, technical and water accounting measures that accurately monitor and incentivize reduced consumptive use.

Box 3. Irrigation efficiency: winners and losers at basin scale

To explain the conundrum that improving efficiency does not necessarily save water and may actually increase water use where the efficiency measures are applied, consider a simplified illustrative case of a small surface irrigation system with low (60 percent) efficiency as shown in 1). The return flows contribute to aquifer supplies available to farmers in a downstream groundwater district. The groundwater available to those farmers consists of natural inflows to the aquifer from connected upstream aquifers, plus the return flows from the surface irrigation district which are originally sourced from the river.



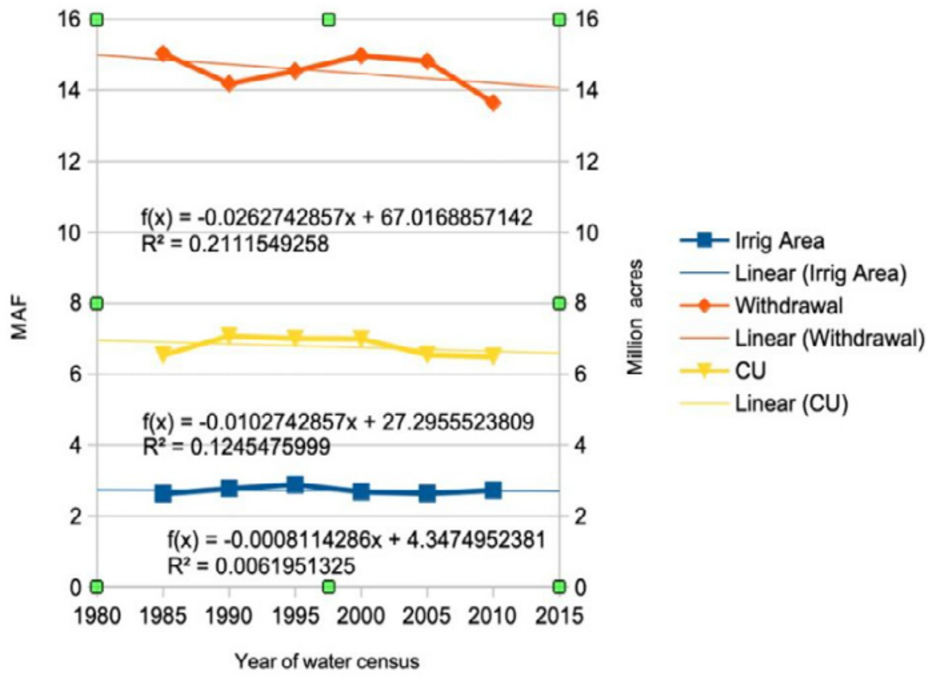
Source: Authors' own elaboration.

When a high irrigation efficiency technology (e.g., drip tape) is applied in the surface irrigation area as shown in 2), most percolation and all runoffs return flows to the groundwater irrigation district cease. Groundwater- dependent farmers thereafter access less water and therefore they produce less. Meanwhile, farmers in the surface irrigation system find they have more water available and so they increase their cropped area or change their crop pattern, or both, in order to profit from the available water.

If canal flows to the surface irrigation area are reduced to 60 units so that they consume no more than before, or if there are strict quotas/licenses in place so that water consumption will remain as before, there is still a need to restore 30 units to the downstream groundwater users, who are isolated from the river system. If in- stream water is needed for environmental purposes further downstream, then further allocation decisions must be made.

Clearly the real world is more complex and the numbers more complicated, but the general principle is well illustrated in this simple and idealized case.

A more recent real-world example is the Colorado Basin, United States of America (Maupin, Ivahnenko and Bruce, 2018). Over the period 1985–2010, water withdrawals for agriculture declined from 15.03 MAF y^{-1} to 13.65 MAF y^{-1} (**Figure 7**), with an additional and proportionately greater reduction in groundwater abstraction relative to surface flows. Sprinkler irrigation was adopted over this period resulting in a decline of 22 percent in surface irrigated diversion in the upper basin with marginal changes in the lower basin apart from the development of micro-irrigation on about 10 000 acres. Over this period, the net irrigated area varied from 2 635 000 acres to 2 891 000 acres with no observable trend (**Figure 7**) and corresponding consumptive use was similarly unchanged, with a very faint downward trend over a range of 6.49 MAF y^{-1} to 7 MAF y^{-1}. In summary, this shows that despite withdrawals decreasing, the net water uses and area remained unchanged, with year to year variability in water resources availability.



CU = consumptive use

MAF = million acre feet

Figure 7 Trends in irrigated area, withdrawals for agriculture and consumptive use, Colorado Basin 1985–2010

Source: Adapted from Maupin, M.A., Ivahnenko, T., & Bruce, B., 2018, Estimates of water use and trends in the Colorado River Basin, Southwestern United States, 1985–2010. U.S. Geological Survey Scientific Investigations Report 2018–5049.

The consumptive use was estimated by traditional water balance methods incorporating the Blaney–Criddle equation for reference ET (ET_0). A parallel estimate in 2010, using the simplified surface energy balance (SSEBop) remote sensing algorithm, did however estimate consumptive use across the whole basin as 21 percent less than that calculated by the conventional method.

2.3.3 Water allocation

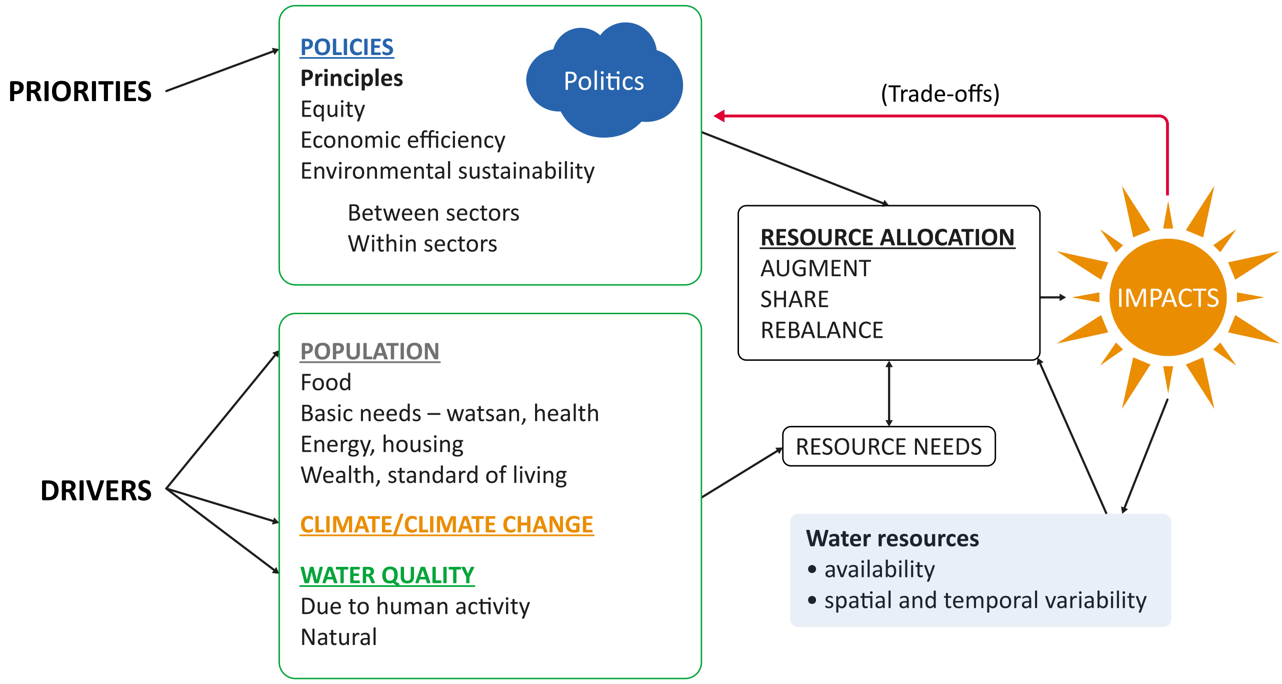
Water allocation is a deliberative process between water planners and administrators and a wide range of users and interests. There are clear physical drivers for demand in different sectors which might include: rates of population growth and consequent demand for food, fibre, heath and sanitation services, amenity, and recreation services; urbanization; industrial development; irrigation water demand; environmental water needs; hydropower production; thermal powerplant cooling; and mining. Two increasingly important drivers are the impacts of climate change on resource availability and use, and water quality, which is emerging as a major concern across Asia (ESCAP, 2020; Damania *et al.*, 2019).

When water is scarce, it is allocated to competing demands through a mix of stakeholder consultation, politics, influence and strategic priorities that are mediated by other sectoral policies and their associated incentives and penalties (**Figure 8**).

The drivers of demand, and their trends, must be understood for long-term planning and sustainable allocation of water resources. It has been argued that formal allocation processes should recognize existing water rights and de facto water use, i.e., established water use that is not necessarily legally sanctioned but is well established (Hodgson, 2016). However, this can in practice be fraught with difficulty in overallocated systems where policymakers must consider how to reduce overall abstractions to a sustainable level in order to protect the resource for future generations.

Indeed, all allocation policies have impacts, which may be considered in terms of equity, economic efficiency, administrative efficiency and simplicity, environmental sustainability and the trade-offs between them (MDBA, 2016; Rosegrant, Cai and Cline, 2002). The impacts and outcomes of water allocation practice can be continually adjusted to optimize benefits in the medium to longer term through adaptive management, although this process is neither trivial nor straightforward in terms of governance (Papas, 2018). When water resources use is unsustainable, reallocation between users is needed, which is inherently contentious, expensive, administratively challenging and may require compensation for losers.

The main focus in water allocation is inevitably on groundwater and surface water resources that can be directly managed by diversion, storage, pumping and conveyance. Flows can be measured easily, although in practice flow measurement is at best patchy and more commonly non-existent. With the ability to estimate actual ET accurately, it is possible to consider the broader basin-scale aspects of water use and allocation in terms of the impacts of land use on evapotranspiration and hence on runoff, catchment yield, groundwater recharge, and in terms of the long-term changes that might increase, reduce, or maintain in- stream and groundwater water availability.



Note: Watsan = potable water and sanitation

Figure 8 General components of a water allocation process

Source: Authors' own elaboration.

It is important to distinguish between **water allocation** and **water distribution**: water allocation is strategic, multijurisdictional and multisectoral and incorporates flexibility in apportioning available water to all users in response to varying supply conditions. Water allocation usually evolves in conjunction with specified water rights in some form and **bulk allocations** may be specified for large or grouped users, such as cities, rural districts, irrigation systems, stock and domestic water supply systems, power companies, sites of special environmental interest and so on. Water **distribution** is the delivery of water to users, preferably in accordance with some allocation process that ensures transparency and equity in the volumes delivered. In larger irrigation systems, ad hoc distribution under varying supply conditions is sometimes erroneously called allocation.

Potable water supply, sanitation and industrial water use are traditionally considered to be non-consumptive, in that evaporation losses are theoretically very low and embodied water contents in industrial products are also small. A key assumption is that water used for these purposes is not sufficiently degraded to prevent reuse, perhaps many times over the span of a river basin. More often than not, this requires primary and secondary treatment of wastewater to ensure acceptable quality of return flows. It is also common for domestic water supply to be used in gardens and for amenity use (public parks, urban tree plantings), which are clearly consumptive uses and need to be accounted accordingly.

Water use in industry and for urban purposes has a high value compared to water use in agriculture. Throughout Asia, as water becomes scarce (particularly in fully allocated basins) water is captured, transferred, or purchased for higher value uses from farmers and irrigation systems (Molle and Berkoff, 2006): since formal allocation procedures are rare and water markets, if they exist at all, are informal and unregulated, chaotic allocation is a likely consequence (Perry, 2019). Private, competitive groundwater use also tends to explode resulting in rapidly declining water tables and subsidence, which can be seen clearly in major cities such as Bangkok and Jakarta.

Historically, since these higher value needs have been small in volumetric terms (~5 percent of water use), the impact on agriculture has not so far been felt at a broad scale, although there is plenty of evidence of gains and losses in farming communities in peri-urban areas that have been overtaken by urban growth, for example in Kathmandu Valley (Thapa *et al.*, 2018). In the longer term, the volume of water required to satisfy high value uses is expected to remain modest throughout much of Asia (<10 percent renewable water resources), and few countries are expected to see the change in balance of water use seen over the last 30 years in northern China (>30 percent RWR) (National Bureau of Statistics of China, 2019).

Box 4. Water allocation and accounting in China

In China, water is allocated to different sectors (agriculture, urban and rural domestic and sanitation, industry, environment and so on) within a limit on total water use (a cap or red line) at national level and in each major river basin. Quotas are issued to each province within a basin and then to each county administration, with defined priorities for high value uses (urban and rural water supply and sanitation and industry). The residual volume is available for irrigated agriculture, aquaculture and other primary production and is allocated annually, also on the basis of quotas (IWHR, 2019).

The mean volume of water resources available at basin and subsidiary levels is updated annually and accounts are also prepared for wet and dry years on record. In practice, interannual variability does not yet feature strongly in the water allocation process. Available water includes water stored in dams/reservoirs and underground. Accounts are also calculated for existing use in all sectors and for predicted demands in the near term and medium term. Where there is interaction between surface and groundwater, more sophisticated assessments of both availability and use are required to avoid double accounting of components of the water balance that occur as both surface flows and groundwater flows. In northern China, water transfers from the Yellow River and the Yangtze River (south –north transfers) are now included in the water resource assessments and are mostly assigned to urban and industrial use and strategic groundwater recharge areas.

The accounts are updated throughout the year and reassessed at the beginning of each water year. Water accounts are typically constructed on the basis of catchment-scale hydrologic modelling, requiring data on rainfall, evaporation and transpiration and streamflow over the entire landscape. In the Hai River Basin, remote sensing is being used to quantify the evapotranspiration from all land cover, allowing better calibration of hydrologic models and also the monitoring of actual water use in irrigated areas (IWHR, 2019).

Water accounting includes sophisticated approaches to demand forecasting on the basis of demographic change, urbanization, industrialization, energy production and irrigation development.

In China, as in nearly all countries in the region, the total volume of water available for human use is limited by its quality, which is affected by salinization, pollution from settlements and industry and from diffuse non-point source pollution from agriculture (Ministry of Water Resources People's Republic of China, undated). Groundwater suitability for certain uses can be limited by the presence of arsenic, fluoride and nitrates, which pose threats to human health. Therefore, water accounting may include assessment, measurement and monitoring of water quality as well as quantity.

References

IWHR. 2019. Consumption-based water management. Zero Draft Discussion Paper. Beijing, China Institute of Water Resources and Hydropower Research.

Ministry of Water Resources, Peoples' Republic of China. undated. Water resources management and protection in China. Brief in English. [online]. Beijing. [Accessed 22 January 2021]. http://www.mwr.gov.cn/english/

Many river basins throughout Asia are already extracting water in a way that is not sustainable in the long term. Sustainable abstraction of groundwater can be set in relation to long--term balance between recharge and abstraction and the economic cost of pumping water from an aquifer. In the Hai River Basin, net water withdrawals have consistently exceeded annual replenishment (Yangwen, 2011), mainly because of mining groundwater resulting in rapidly falling water levels. The prime target of water accounting and the associated allocation processes is to bring groundwater use within sustainable limits, principally by reducing agricultural use of groundwater through quotas and in some cases through land retirement, and by augmenting surface supplies and recharging groundwater with water transferred from the distant Yangtze River.

A key lesson from the Chinese experience in water accounting concerns the timing of water accounting and allocation initiatives. If a full understanding of the water resource is achieved before water scarcity is severe, interventions to address overuse are easier and less costly to design and implement.

2.4 Managing water consumption

CBWM focuses on abstracted surface water and groundwater for irrigation as the main consumptive use of water resources. Manageable consumptive use by crops and pastures can be assessed by measuring or calculating actual evapotranspiration (ETa). Other methods are required to assess the portion of consumptive use in domestic and industrial water supply – a potentially complex process of tracking embodied water, polluted wastewater and garden and amenity water use that account for a small fraction of a typical national water budget (< 5 percent in most of Asia).

Consumption-based water management (CBWM) in China (IWHR, 2019; World Bank, 2011b; World Bank, 2013) incorporates:

- an understanding and assessment of actual agricultural (and environmental) water demand in a basin (this is based on a reference assessment and attribution of current consumptive use across a river basin and prediction of water demand from climate data and expected crop patterns);
- planning and controlling actual water use to limit consumption within the framework of a cap at river basin or catchment level and subsidiary quotas at local and system level down to water user groups and individual farmers, depending on scale (this requires allocation of high priority water use and specification of agricultural allocation for a river basin and its sub-catchments, and political – administrative jurisdictions and setting of ET quotas and respecifying them in terms of diverted or delivered water);
- monitoring actual use using remote sensing methods (adjusted for effective actual rainfall); and
- incentivizing quota compliance and penalizing excessive use.

In China, these components are carried out as top down and bottom-up processes, in that local estimates of demand are made in parallel with global calculations from the river basin authority, within the context of an established water allocation framework (IWHR, 2019). In other circumstances CBWM would be fitted into the existing water allocation framework although there might be more stakeholder involvement and deliberation.

2.4.1 Direct measurement of actual evapotranspiration

Over the past 20 years, there has been fruitful research on the estimation of actual evapotranspiration (ET_a) from satellite-borne sensors to the point that remote sensing of ET_a (RS-ET_a) is a mature and practical technology, although with some practical limitations because of cloud cover restrictions on earth observation, especially in the humid tropics.

Prior to the development of energy balance methods to estimate ET_a, crop water use could only be predicted from evaporation pans (with suitable crop factors) or forecast from sparse agro-meteorological data and experimentally derived crop factors.

Usefully, global data to determine ETa is available for free, at a range of time intervals and resolutions that allow timely and continuous analysis. Automated online procedures continue to be developed to improve timeliness and ease of analysis and free global ETa products are also available from FAO's WaPOR service (FAO, 2021b) although for Africa only at the moment. There is also the OpenET platform (Openet, 2021) and the EEFLux platform (https://eeflux-level1.appspot.com/).

China is a leader in the development and use of remote sensing technology to manage water consumption in the Hai River Basin and in the Turpan (groundwater) Basin in Xinjiang Province, using a suite of tools known as ETWatch (Wu, 2012), which has been developed for multiple scales of analysis by the Chinese Academy of Sciences, based on science and modules developed in China, the Netherlands, and the United States of America. Detailed procedures for managing consumptive use have been developed by IWHR and other research institutes for basin level assessment and for implementing, monitoring, and controlling water use in 16 counties in Hai Basin and over the entire Turpan Prefecture. In at least two pilot cases, water quotas are set, monitored and managed for individual farmers. CBWM is scheduled to be rolled out across all counties in the Hai River Basin and will be trialled in the Yellow River Basin, where smog and cloud cover present significant challenges throughout most of the year.

2.4.2 Water productivity and water use

Much has been written, rewritten, and misinterpreted on the subject of water productivity and the potential to save water through more efficient crop water use (*Giordano and Villholth*, 2007; *Perry and Steduto*, 2017). It is indisputable that globally and regionally more food will need to be grown with less or the same amount of water to meet future food needs. This is an increase in crop water productivity, measured in terms of product produced per unit of water consumed (kg m^{-3}). There are other useful metrics of water productivity relating to nutrition, energy requirements, and importantly from a farmer's perspective, monetary income.

At the field scale, a farmer's main goal is to generate more income and, at a minimum, provide more food for subsistence. Most farmers in Asia have small landholdings and are therefore predominantly interested in maximizing yield (kg ha^{-1}). Although water supplies may be inadequate and erratic, farm production is still constrained by area. In contrast, large farmers in a country such as Australia may have an excess of land relative to their water entitlement. Recently Australian irrigators have become very interested in maximizing dollar water productivity as a means of maximizing their income. Rainfed cereal growers in the same country have long been interested in maximizing water productivity in response to limited rainfall (Sadras and McDonald, 2012; Sadras, Grassini and Steduto, 2007).

All things being equal, yield is linearly correlated to water use (ET), so increasing yield with adequate nutrition and plant health implies using more water with declining water productivity as yields increase (Perry *et al.*, 2009). Logically, farmers' interest in increasing yield and income therefore results in increased water use. In practice there is a great range of yield and water productivity determined from farm data (Bastiaanssen and Steduto, 2017; Batchelor and Schnetzer 2018; IWHR, 2019), which does in fact present opportunities to both increase yield and water productivity on average and produce more food with less or the same amount of water through optimizing all factor inputs of crop production (van Opstal *et al.*, 2021).

Translating improvements in water productivity into real water savings requires careful analysis and clear targets such as increased production at a given location, water reallocation to irrigation elsewhere in a basin to increase overall production, or water reallocation to other uses. As with efficiency measures, some form of restriction of supply (quota) is needed if real water savings are to be realized in practice (van Opstal *et al.*, 2021). In the north China plain, where groundwater restrictions are being imposed, farmers are being encouraged to grow one crop of cotton per year in place of winter (irrigated) wheat and summer maize that is mostly rainfed. The net income from cotton is higher than for the wheat–maize crop pattern and uses up to 30 percent less irrigation water. A real water saving is realized by reducing quotas for adopters, while incentivizing them with zero water fees. Crop ET is monitored by routine RS-ET measurement and penalties are applied for exceeding the quota for water use (IWHR, 2019). Such farmers may purchase food and have surplus income, but many prefer the security of growing their own food.

2.5 Conclusions

CBWM provides a sound basis on which to set and manage irrigation quotas and to restrain water use in a river basin. Its focus on estimating actual ET allows a better understanding of water conservation impacts and strategies to increase food production under conditions of water scarcity.

The remote sensing of evapotranspiration for the assessment of consumptive use can play an important role in constructing preliminary water balances and water accounts and in monitoring actual water use. Many factors will determine when and if countries wish to adopt CBWM, and in the meantime there will be much to learn from its evolution in China, United States of America and Spain.

Chapter 3. Law, policy, governance

3.1 Introduction

It is widely recognized that water scarcity and its associated challenges are a crisis of governance (Asian Development Bank, 2013) rather than one of availability.[1] As stated by Graham (cited in Jiminéz *et al.*, 2020, p. 2), "the interactions among structures, processes and traditions that determine how power and responsibilities are exercised, how decisions are taken and how citizens or other stakeholders have their say" have in many instances led to overextraction and iniquitous water sharing arrangements (both formal and informal).

Purely technical discussions about water are therefore unlikely to address the underlying drivers of water scarcity and water poverty and, to that extent, risk generating solutions that are theoretically sound but practically ineffective.

This reasoning extends to regulatory frameworks that are poorly implemented because of, for example, inadequate or absent monitoring, institutional deficiencies and more general socioeconomic and political barriers. Indeed, despite a proliferation of environmental laws since the first Earth Summit was held in Rio de Janeiro in 1992, environmental degradation (which includes overexploitation of surface and groundwater resources) has continued apace. In 2019, the United Nations Environment Programme (UNEP) formally acknowledged the various governance issues which result in poor implementation of environmental laws in its report entitled *Environmental rule of law: first global report*. This report sets out a series of recommendations intended to address these underlying problems, some of which will inform the discussion and recommendations in this chapter.

Against this backdrop, it is clear that any meaningful discussion of CBWM must not only contemplate the regulatory framework required to facilitate such a technically sophisticated method of water management, but the broader governance challenges associated with its actual implementation. In making this observation, we note that the legal–political context within which CBWM operates in China is relatively unique and that the level of technical expertise within relevant government agencies in the Turpan Prefecture and the Hai River Basin is high (and that those agencies are supported by leading experts in universities, the China Institute of Water Resources and Hydropower Research and the CAS Water Resources Research Centre). We further note that attempts to directly transplant systems of water management from one context to another without proper consideration of the local legal system (or systems, as the case may be), cultural norms, institutional capabilities and other enabling conditions and/or barriers are generally doomed to failure. Put simply, what works in one country may not work in another – or may only work once the necessary enabling conditions are in place or adjustments are made to accommodate local differences and preferences.

Accordingly, the purposes of this chapter are as follows. First, it will set out the legal and broader governance framework that has enabled CBWM to operate in the two pilot provinces in China. Second, it will extract from this and other data a set of enabling conditions required to facilitate the successful development and implementation of CBWM in different settings in Asia, and the extent to which these conditions can be adapted to suit local conditions and norms. Finally, it will use case studies of Afghanistan and Cambodia to illustrate the governance challenges and barriers – and conversely opportunities – that may arise when attempting to implement CBWM in new contexts.

1 The apparent contradiction between this statement and the previous emphasis on overallocation of water in river basins can be explained thus: any expression of water scarcity for high-value uses (WASH, industry, amenity, energy production) is (because of its modest volumetric requirement) a failure in governance. Physical water scarcity should affect the large volume water users – irrigated agriculture and the natural environment. Insufficient water allocation to maintain a healthy environment is likewise a failure of governance.

3.2 Water law in China: an overview

CBWM sits within a hierarchical system of water regulation and administration which has evolved over the last three decades in particular (Figure 9). Although this system has not historically provided for CBWM, it has been adapted to allow for such a framework to be implemented in the Turpan Prefecture in the Xinjiang Uygur Autonomous Region and Hai River Basin. This has been made possible by the presence of several key features which include: a system of bulk water rights capable of being adapted to accommodate an ET- based system of yearly water quotas; water pricing, including punitive pricing for water users who exceed their annual allocation; basin-level water use quotas which, first, set an overall cap on extractions and, second, allocate water between different sectors (including agriculture) within the limits of that cap; market-based mechanisms which allow for water trading in certain circumstances; and compliance and enforcement capacity (World Bank, 2013; Jiang, 2018; Moore, 2019). The following paragraphs will explore elements of this system in more detail.

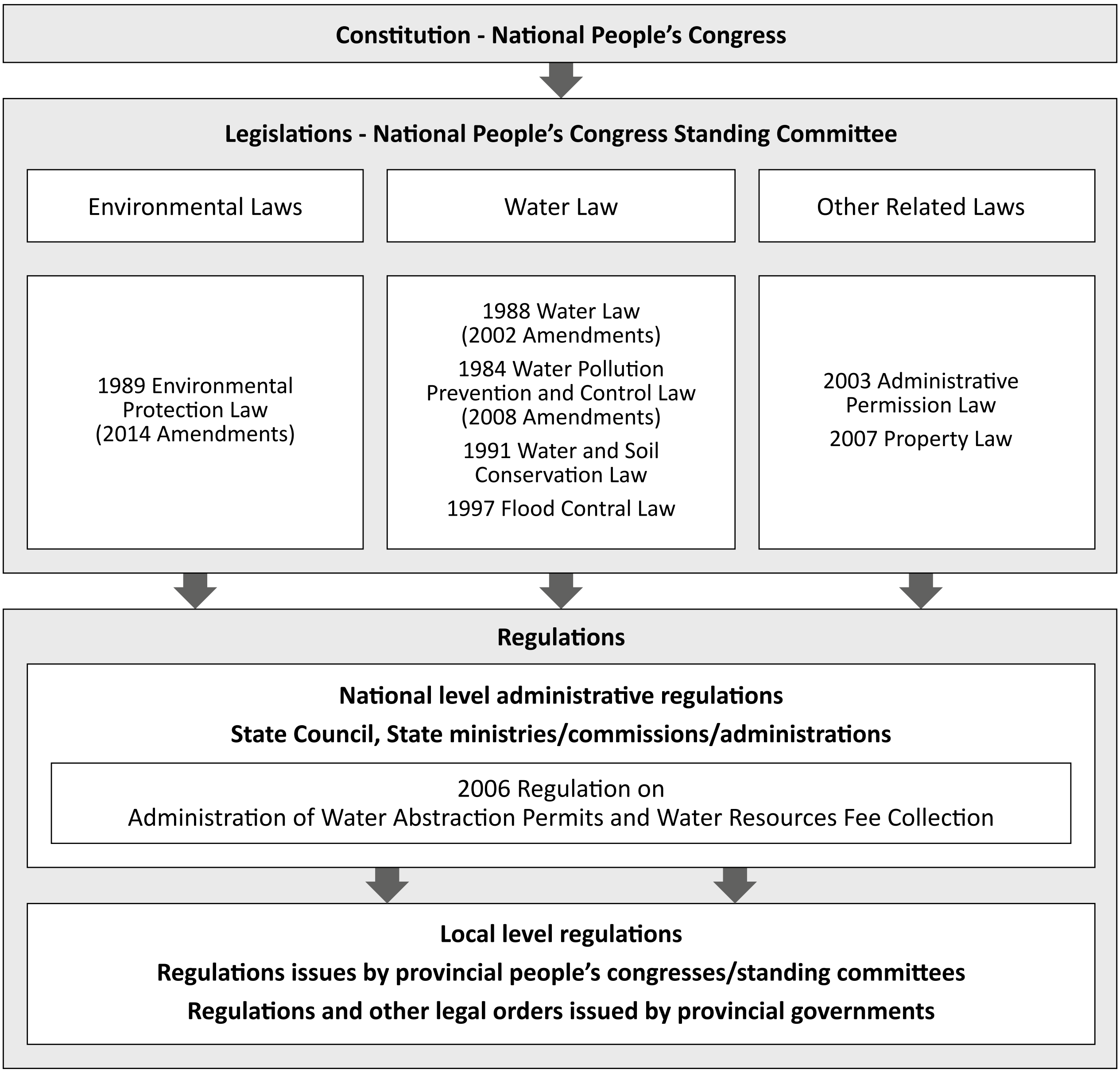


Figure 9 Water laws in China

Source: Jiang, M. 2018. Recent developments of water trading in China. University of Nottingham: Asia Research Institute. Available at http://theasiadialogue.com/2018/05/29/recent-developments-of-water-trading-in-china/.

As in many countries, water law and policy in China consists of several layers which become more granular and context-specific at the provincial and local levels. At the apex sits an overarching policy known as the “most stringent water resource management system” or the “three red lines”. Adopted in 2012, it sets targets for total water use, water use efficiency and water quality at the provincial and county levels for a number of benchmark years to 2030 (Moore, 2019; Zhang, Chen and Zhu, 2018). The three red lines are complemented by the national Water Law of the People’s Republic of China (Water Law) which was originally adopted in 1988 and then revised in 2002. The Water Law comprises 82 articles which *inter alia* nationalize all water (Article 3); require most forms of usage to be licensed and paid for (Article 7); mandate the adoption of total extraction limits and within these limits, sectoral water use quotas at the provincial and county levels (Article 47); provide for basin-scale planning and management (Article 12); provide for environmental flows (Article 21); and set out a civil and criminal penalty framework for illegal activity (Article 65 and Article 66).

The objectives of the three red lines and the particulars of the Water Law are enlivened by a number of other laws and regulations, beginning with two non-environmental, national level statutes and two complementary regulations adopted in 2006 and 2016 which have resulted in the progressive expansion of water rights trading.

The first of these statutes, the 2003 Administrative Permission Law of the People’s Republic of China (Administrative Permission Law), provides for administrative licensing across a range of areas, including water abstraction licenses. The Administrative Provision Law prohibits the transfer of administrative licenses unless explicitly authorized by another law (Article 9). Explicit permission to trade in certain circumstances was initially provided for in the 2006 Regulation on Administration of Water Abstraction Permits and Water Resources Fee Collection (Abstraction Permits and Fee Collection Regulation) (Article 27). This in turn resulted in a series of pilot water trading programmes, debuted across seven provinces in 2014 (Moore, 2019).

The 2016 Provisional Measures on Administration of Water Rights Trading (Provisional Water Rights Trading Regulation) significantly expanded upon the types of water trading permissible in China and provided for the creation of a national water exchange. More specifically, the new regulation established three types of permissible trading, namely regional water rights trading, water abstraction rights trading between permit holders (excluding urban water suppliers), and water rights trading between irrigators (that is, between water users’ organizations or individual users) (Jiang, 2018). The second statute, the 2007 Property Law of the People’s Republic of China (Property Law), reiterates that water resources are the property of the state (Article 46) and accords third parties usufructuary (or usage) rights in relation to the state’s water (Article 118). The Property Law also states that water abstraction rights are protected by law (Article 123).

Together, these laws and regulations establish a high-level legal framework for water licensing, which is a foundational component of CBWM. They also notionally facilitate trade, which when combined with water allocations based on water *consumption* (as measured by ET) rather than *withdrawals* can be used to complement the objectives of CBWM.[2]

As noted above, national legislation and regulations are implemented by a suite of water- specific laws and rules at the provincial, prefecture and county levels. These laws and rules address issues such as local water planning and establish detailed frameworks for water abstraction permits (Liu and Speed, 2009). It is beyond the scope of this document to address all of these laws and rules, or the challenges that may arise as a consequence of this layered legislative framework, such as local resistance to national directives (Moore, 2019). However, the case study of the Turpan Prefecture provides an example of how provincial and prefecture-level water laws and institutions seek to implement higher order legislation – and how such a system can be adapted to facilitate CBWM.

2 In making this observation, we note that ET per se cannot be traded or distributed through an irrigation system. Rather, it can be estimated, converted into a volumetric allocation for delivery to a water user and subsequent withdrawal and objectively monitored over time.

3.3 Institutional framework: an overview

China has five administrative levels which span the national, provincial, prefectural, county and township administrations, with "each level answerable to the superior level of government" (Shen and Speed, 2009). Institutional water governance corresponds to these administrative units, with responsible agencies spanning the national to county levels.

However, it is also organized around hydrological units (river and lake basin commissions) and irrigation districts or townships (water user associations or WUAs), giving rise to a complex and sometimes overlapping set of competencies and responsibilities (Yao, Zhao and Xu, 2017).

The overarching administrative body responsible for water management in China is the Ministry of Water Resources of the People's Republic of China. The Ministry is divided into various sub-departments that are charged with a range of matters including but not limited to implementing the three red lines and the Water Law; developing laws and policies; high-level water planning; managing water abstraction permits; hydrology; and flood mitigation (Ministry of Water Resources, undated; Leu and Speed, 2009). The Ministry has further established seven river and lake basin commissions which are responsible for planning, monitoring and enforcement in their respective basins (Jiang, 2018).

Water agencies (usually known as water resource bureaus) at the provincial, prefecture and county levels also play a key role in relation to matters such as water planning, permits, use and dispute resolution (Jiang, 2018; Liu and Speed, 2009). Finally, user-based, participatory management units known as water user associations (WUAs), the geographical representation of which varies, but which may sit within irrigation districts or townships[3], have spread across China over the last few decades. WUAs were originally developed and implemented in cooperation with the World Bank in the late 1980s and either sit alongside, or have entirely replaced, more traditional village water user committees (Zhang *et al.*, 2013). WUAs are not homogenous in their structure or function but may undertake activities such as water distribution between farmers, canal management and fee collection to maintain irrigation infrastructure in the district (World Bank, 2011b). As discussed in the case study below, they have played a key role in the implementation of CBWM in the Turpan Prefecture.

Although it is also beyond the scope of this chapter to examine the challenges associated with this "complicated hierarchy" (Jiang, 2018), it is worth noting that this framework reflects two overwhelmingly positive features, namely the evolving nature of water governance in China and the country's considerable bureaucratic and technological capacity. Both of these factors have proven an asset for the purposes of developing CBWM in the Turpan Prefecture and Hai River Basin.

It would not have been possible to integrate CBWM into existing governance frameworks if, first, there were no appetite to evolve and adapt in response to water scarcity in these regions and, second, there were a dearth of resources to develop and implement such a technologically advanced system. Furthermore, the centralized system of governance has also allowed for greater control in relation to the types of crops grown and the total area under irrigation (Yao, Zhao and Xu, 2017). Again, both of these have enabled the development and implementation of CBWM and as such will be discussed in more detail in the case study on the Turpan Prefecture.

3 Note that most WUAs are established under water agencies at the county level (for example) or under villages (World Bank, 2011a).

3.4 Water allocation in China: an overview

Water allocation policy in China follows the legal and institutional hierarchy outlined in Section 3.2 and Section 3.3, above. In the first instance, the Ministry of Water Resources is responsible for setting overall water use limits, known as total amount control (TAC), which are in turn translated into water allocation plans and within those plans, sectoral water use quotas at the basin, provincial, prefectural and county scales (as per the requirements of the Water Law). The TAC, allocation plans, and sectoral quotas are generally set to balance average water resources availability with demand: high priority is accorded to water demands for urban, industry, power and a modest environmental flow allocation, with the residual water allocated to agriculture. Quotas devolve all the way down to WUAs and individual users, all of whom are required to hold a valid water abstraction permit (again in line with the Water Law) (Yao, Zhao and Xu, 2017; Shen and Speed, 2009).

Although further work is required to link environmental flow allocations with ecosystem requirements (Shen and Speed, 2009), the setting of TAC and quotas is nonetheless an indispensable component of successful CBWM. That is, for CBWM to successfully address overextraction it must sit within a broader framework that includes sustainable extraction limits and reserves a volume of water for basic ecosystem needs and/or to meet groundwater recharge requirements. At the moment these extraction limits are set on the basis of average water availability and are not adapted to interannual variability, nor do they involve more than a very modest environmental water allocation.

3.5 Pilot projects

China has a history of using pilot projects across different provinces, geographies, climates and socioeconomic contexts to test the validity of a particular water policy framework before committing to broader regulatory change. For example, pilot projects have been run across different catchments in China in relation to integrated river basin management (IRBM) (te Boekhorst *et al.*, 2010) and environmental flows (International Water Centre, undated). More recently, and as noted above, the Provisional Water Rights Trading Regulation, which was adopted in 2016, was preceded by water trading schemes that had been piloted across seven different provinces. The implementation of CBWM in the Hai River Basin and Turpan Prefecture is arguably the most developed and technologically advanced example of this pilot-based approach, and one that has allowed for different assumptions to be tested and the system to be adjusted over time. It is important to keep this in mind when considering how CBWM might be developed and implemented in different countries and contexts (noting that pilot projects that depend exclusively on external funding and expertise are unlikely to be successful in the longer term).

Box 5. Case study A: Consumption-based water management in the Turpan Prefecture Background

Background

The Turpan Prefecture is located in the hottest and driest region in China, namely the Xinjiang Uygur Autonomous Region in arid northwestern China. It consists of two river basins: the Dzungaria (or Jungaar) Basin in the north and the Tarim Basin in the south. The former is largely endorheic (i.e., has no outlet); the latter is entirely endorheic.

In recent decades, water scarcity has been exacerbated by overextraction for irrigated agriculture. Specifically, a local policy introduced in the middle of the 1980s to attract commercial growers of high value horticultural produce from outside the region has resulted in the rapid overdraft of groundwater (which is the principal source of water for irrigation). Furthermore, the regulatory framework incentivised farmers to "use or lose" their water allocation, resulting in additional extractions (Li *et al.*, 2020).

Legal and governance framework

The Turpan Prefecture Water Resources Bureau (TPWRB) is the overarching administrative body responsible for water management in the Turpan Prefecture; it is also responsible for adopting locally specific regulations that implement the Water Law, three red lines and other national laws and policies. Accordingly, it implements the water withdrawal permit system, collects water charges, water resources fees and water resources compensation fees, and administers permits for the construction of wells. It also oversees county water bureaus, to which it delegates certain functions.

An important component of the legal and governance framework is the adoption of local water allocation plans which set limits on water extractions and apportions water between sectors, including agriculture. These allocation plans are constrained by an overall basin-wide water use quota set by the regional government. The autonomous region was one of the first administrative areas in China to adopt basin-wide quotas and local water allocation plans, including for the Turpan Prefecture. However, according to the World Bank (2013), quotas have not been strictly enforced, resulting in continuing groundwater overdraft. In 2009, the prefecture also adopted the Implementation Measures of Turpan Prefecture for Groundwater Resources Management.

These measures mandated water-savings techniques compatible with ET-based policies, such as a reduction in groundwater extractions, adjustments to cropping patterns, supply quotas, surface water augmentation and, in some cases, closure of wells and retirement of land.

Consumption-based water management within the existing governance and legal framework

According to the World Bank (2013), a number of legal and governance deficiencies have contributed to the overdraft of groundwater in the autonomous region. Notably, groundwater extractions have not been properly measured, there may be no reliable record of water permits issued and overall quotas have not been enforced. Furthermore, irrigation upgrades designed to increase water efficiency have not considered return flows, resulting in crop expansion and increased extractions. Finally, the permitting system only provides for water withdrawn and to that extent does not yet factor in ET or return flows.

Notwithstanding these limitations, the fact that the law provides for basin-wide quotas, sectoral water use allocations and water licences subject to extraction limits has meant that the regulatory framework could be adapted to introduce CBWM.

The existence of a groundwater policy compatible with ET-based water management practices has also proven advantageous. Some of the regulatory adjustments that the World Bank (2013) advised would be required to fully implement CBWM in the Turpan Prefecture include:

- setting basin-scale quotas followed by water rights allocation plans for the three geographical areas of the prefecture, with these being based on ET targets for irrigated agriculture;
- defining water rights in terms of water extractions and consumption (which accordingly factors in return flows) – again, based on ET targets for irrigated agriculture;
- providing for the reallocation of water rights from one user to another (rather than the creation of entirely new rights); and
- water rights supervision, in particular in relation to the new elements of the water right, namely the
- volume of water extracted, the volume consumed and the quantity and quality of return flows.

These legal adjustments are in theory supported by bureaucratic and technical capability at the national, prefectural and county levels. For example, the TPWRB has established an ET monitoring centre, which is assisted by the Chinese Academy of Sciences (CAS), and the Shanshan County Water Bureau is responsible for issuing yearly allocations to water rights holders in that county and assessing compliance with the core elements of those rights.

Challenges

A significant reduction in the total irrigated area is required to achieve sustainable groundwater use, and this is proving administratively challenging because of the formal allocation of licenses to commercial growers who were invited to the province.

Furthermore, issuing yearly water use allocations to the holders of water rights on pieces of paper, and then verifying the three core elements of those rights (withdrawal, consumption and return flows) imposes a significant administrative burden on water agencies. This arguably requires reform to ensure that the system is efficient and manageable.

References

Li, Y., Wang, H., Chen, Y., Deng, M., Li, Q., Wufu, D., Wang, D. & Ma, L. 2020. Estimation of regional irrigation water requirements and water balance in Xinjiang, China during 1995–2017. PeerJ 8 e8243. [online]. [Accessed 22 February 2021]. https://peerj.com/articles/8243/

World Bank. 2013. Design of ET-based water rights administration system for Turpan Prefecture of Xinjiang China. Washington DC.

3.6 Key legal and governance requirements for consumption-based water management

Consumption-based water management (CBWM is a sophisticated, technology-dependent form of water management. As such, a number of fundamental legal and governance elements are required before CBWM can be implemented and yield results (that is, generate real water savings and combat overextraction and associated water stress in affected regions). Some of these elements have been touched on in the analysis of Chinese water law outlined in Section 3.2, Section 3.3 and Section 3.4 and in the case study of the Turpan Prefecture. However, this section will address these factors in more detail.

3.6.1 Ownership of land and water

The first issue to consider is that of ownership, control, and use of the waters within a particular locality. In China, all water is owned by the state (Water Law, Article 3), with its use by individuals, WUAs or industry being conditional upon the acquisition of a water permit and compliance with relevant conditions and regulations. This use occurs within the context of TAC and sectoral water quotas that cascade from the basin scale down to the county level. This overarching system allows the state to amend the law to accommodate a form of water management – namely CBWM – that involves a high degree of control over how much water is used, when and by whom. Although CBWM could be implemented in different legal systems, it is nonetheless important to consider the extent to which the state is able to regulate water use in this manner.

Any such assessment would need to consider the relationship between land tenure and water in another Asian country. For example, it may be difficult to insert CBWM into a legal system that has adopted a full flow version of riparian water rights, according to which the riparian land holder is entitled to the full flow of water passing by or beneath their property, as opposed to being limited to reasonable (or regulated) use of the flow. For a discussion of the adoption of full flow riparian rights by Indian courts – and attempts to introduce regulated riparian rights in certain Indian states – see Richardson (2017).

An assessment of the relationship between land tenure and water would also need to consider the possible intersection between different legal systems within a single country and the impact of this intersection on the control and use of land and associated waters. For example, in Afghanistan land and water management sits at the intersection between the national civil code, the 2009 Water Law, various presidential decrees, property and succession law, customary law, and Islamic law and jurisprudence. It is not uncommon for land ownership to be contested, which in turn gives rise to conflict over who is entitled to use proximate surface water and groundwater (Stanford Law School, 2015). This level of complexity in land tenure and water management arrangements would probably prove incompatible with CBWM, which as noted above requires the state to be able to control when and how much water is used in order to generate real water savings.

3.6.2 Water laws and associated governance mechanisms

Water laws can encompass a range of possible forms. These include formal, codified systems embedded in national constitutions and/or statutes that are passed by national, provincial or county governments, customary water laws that may be codified or oral, or both, and religious laws, such as Islamic law and jurisprudence. In some countries, the national constitution or other legislation may recognize customary laws, giving rise to a hybrid system of water management. In others, all three systems may exist and, in some instances, overlap.

It is important to note that customary laws are often sophisticated and based on a detailed knowledge of local conditions (Craig and Gachenga, 2009; Ramazzotti, 2008). Similarly, Islamic jurisprudence and dispute resolution may play an important role in determining how land and water are managed in certain places (Stanford Law School, 2015). However, the technical nature of CBWM is such that it is best implemented within the context of a formal, codified system that has been adopted by the appropriate level of government. Although the framework can be flexible enough to take into account local contexts and cultural norms (World Bank, 2011a), and ought to carefully consider any interaction with customary or religious laws, it should provide for the elements set out below.

Sustainable extraction limits

CBWM is a system of water management that must exist within the context of an overall limit on water extractions (sustainable extraction limits) if it is to be successfully implemented and generate real water savings. To that end, the law should provide for sustainable extraction limits to be imposed at hydrologically relevant scales (basin and catchment levels) rather than on the basis of administrative units (Aither, 2018a). The purpose of such limits is to reverse historical patterns of overextraction and facilitate sustainable management of freshwater resources. This requires a certain volume of water to be reallocated to the environment. This is discussed in more detail in the subsection dealing with environmental flows, below.

Determining sustainable extraction limits is a complex process which requires consideration of available scientific evidence and other locally relevant socioeconomic and cultural factors (Anderson *et al.*, 2019). In many river basins in the Asia–Pacific region, hydrologic and related ecological data is relatively poor, thereby necessitating investment in monitoring, hydrologic and climatic modelling and other research to better understand current and future water availability under different climate scenarios, ecosystem health and so on (Asian Development Bank, 2013). This information can be used to inform and update sustainable extraction limits over time. The law can accommodate this approach by requiring extraction limits to be amended as new information becomes available.

However, it is not uncommon for overallocation and insufficient data to go hand in hand. As a consequence, waiting for exemplary data sets in a changing climate will only serve to further undermine water security and expedite ecosystem collapse. In such instances, expert opinion can be sought from experienced local and regional specialists regarding possible legal and policy settings (Asian Development Bank, 2013) with a view to preventing ongoing decline. This approach is closely tied to a legal concept known as the precautionary approach or the precautionary principle. According to the Rio Declaration (Principle 15), the precautionary principle acknowledges that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNEP, 1992). Again, this can be accommodated in the relevant legislative schema (as is the case in many parts of the world, including Australia and the European Union).[4]

Given these variables, the law may or may not prescribe a precise method to determine basin-wide or catchment-wide sustainable extraction limits. However, it should require consideration of both historical and future climate data with a view to ensuring permissible extractions diminish as water becomes increasingly scarce. This may also require an increasingly large percentage of available water to be reallocated to the environment to maintain ecosystem resilience in a changing climate (Pittock, Grafton and Williams, 2015).

Sectoral limits on extraction

As CBWM is a system of water management that is informed by ET and applies specifically to crop production, it may be necessary for the law to allocate water to non-agricultural sectors (within the context of basin and catchment level sustainable extraction limits and environmental flows).

Environmental flows

Environmental flows are defined as the quantity, quality and timing of water required to sustain freshwater ecosystems and the human beings that depend upon them (Linstead, 2018; Horne *et al.*, 2018; International River Foundation, 2007). As sustainable extraction limits, determining environmental flows in a changing climate is a complex process that should ideally be informed by reliable data. Where quality data is absent (as is often the case), research and development ought to occur. However, and as noted above, the absence of data should not act as a barrier to action: where ecosystem decline and unsustainable groundwater depletion is apparent, a precautionary approach should be adopted.

A key issue for policymakers and stakeholders is whether the volume of water reallocated to the environment for environmental flows is represented in law as an average volume over a specified period of time. A system of this nature would allow yearly extractions to vary according to seasonal water availability – as long as the volume of water set aside for the environment is on average maintained over the requisite timeframe.[5] If such a system is adopted, care should be taken to ensure that it takes into account climate change (that is, the volume reallocated to the environment includes due consideration of probable, future reductions in water availability) and that core components of the flow regime (low flows, first flows after drought, overbank flows) are legally protected from extraction (Kimura de Freitas, 2008; Carmody, 2019). Furthermore, it may be necessary to consider whether ancillary actions are required to maximize the benefits of environmental flows, such as the strategic removal of levee banks from floodplains that would otherwise impede the movement of water (Carmody, 2017).

Reallocating water to the environment can be contentious as it involves reducing the volume of

4 See for example: *Environment Protection and Biodiversity Conservation Act 2000* (Cth) (Australia), section 391; *Treaty on the Functioning of the European Union*, Article 191 (Europe).

5 This would also require the sustainable extraction limit to be set as an average to be complied with over the requisite period of time. This is the system followed in the Murray–Darling Basin, Australia.

water that is available for different consumptive uses. This can give rise to strong opposition from stakeholders (in particular large consumptive users) which can translate into a lack of political will on the part of governments to implement such changes (Hanemann and Young, 2020). There may also be a wide divergence in views between different stakeholders as to what constitutes a healthy river or freshwater ecosystem (Bunn, 2003). Decisions to reallocate water to the environment and preserve environmental flows may therefore benefit from the deliberative approach outlined in Section 3.7.1 (supported by information about ecosystem services, as outlined in Section 3.7.2).

Licensing and seasonal allocations

CBWM involves controlling the volume of water that is not only diverted, but consumed, by water users, which in turn requires due consideration of return flows. The precise and technical nature of CBWM accordingly calls for a formal licensing system that is capable of providing for these three elements. This could involve a bulk licensing regime under which water is assigned to a water user group or irrigation area, and then distributed amongst individual users within the group or area depending on their licensed share of the bulk volume. Equally, it could involve a system whereby water is directly allocated to each individual license holder. However, in any context with large numbers of very small farmers, bulk allocation is preferable, not least of all because the transaction costs of individual licensing are an impediment to implementation.

In either instance, the bulk or individual license should provide for a variable share of the available water resource rather than a fixed, yearly volume. This is because CBWM should depend on annual (or seasonal) determinations of how much water is available to be diverted and consumed on the basis of ET data for a given area.

Licensing would ideally be managed on computerized databases that allow for changes to yearly water allocations to be updated without having to continually issue pieces of paper to license holders (which would rapidly become unwieldy in any system with thousands of water users). Where an electronic system is feasible, texts and/or emails could be sent to water users informing them of seasonal allocations and any other relevant information (Abubakr, Haider and Zahoor, 2016). In making this recommendation, we note that not all water users have internet or computer access or are literate. These are challenges that arguably require systemic solutions, proper exploration of which lies beyond the scope of this document. However, such barriers must be identified and addressed in the appropriate manner.

Such a system should be supported by an online, public register for all licenses in a designated area to ensure transparency and lawful administration of the licensing system. A register of this nature would allow users and other interested parties to view all licenses, yearly allocations and license conditions. If it is considered inappropriate to publish the names of individual license holders, each license could be identified by an administrative number. It could also include all temporary and permanent transfer of water and all environmental water use.

Measurement, accounting, auditing

Effective implementation of CBWM requires individual and/or bulk water extractions to be accurately measured; this is also necessary for compliance and enforcement purposes (as discussed below). The law could therefore require measurement of extractions by individual users, a water user association or irrigation area, or a combination of both.

It may also prescribe the method of measurement or leave this to the discretion of local authorities (taking into account what is practical in the circumstances, including the cost associated with a particular method). Methods of measuring water extractions include meters and remote sensing (where persistent cloud cover does not impede the use of the latter). It is worth noting that telemetry has been used in parts of Asia, including Pakistan, to measure flows in irrigation canals and assess this data against intended deliveries to different parts of the system (Abubakr, Haider and Zahoor, 2016). However, metering and telemetry require ongoing funding for maintenance, appropriately qualified experts capable of installing and repairing the instruments and access to replacement parts. Meters should also be tampered proof (via seals, locks or other mechanisms) to avoid false readings which underestimate the volume diverted (Irrigation Australia, undated).

Adherence to a sustainable extraction limit also requires measurement of overall water extractions at the catchment and basin scales. Hydrological models are generally employed for this purpose. However, they can vary considerably in their accuracy. For example, models can underestimate catchment-wide or basin-wide extractions and thus overestimate the volume of water that has been made available for the environment over a given period of time (Wheeler *et al.*, 2020; Wentworth Group of Concerned Scientists, 2020). In systems where diversions are estimated by hydrology, this can undermine the accuracy of water accounts (which are designed to represent various elements of the water balance at specified intervals, often yearly).

Accordingly, water accounting, even in countries where it is well established, requires continual improvement in data coverage (spatial and temporal) and, where necessary, the use of well-calibrated substitute data such as that derived from remote sensing.

Improvements are also required in data quality and reliability (meter calibration and maintenance), in data accuracy, and where necessary, in hydrological representation in simulation models and adequate model calibration.

Compliance and enforcement

The successful implementation of CBWM depends on individual license holders and/or bulk license holders for a particular water user group or irrigation area complying with legally mandated extraction limits. It is therefore appropriate for the law to include a suite of relevant offence provisions, including for extracting more water than is permissible under a given license. Penalties should also be sufficiently high so as to act as a deterrent. This requires consideration of the economic gain associated with unlawful extractions (Loch *et al.*, 2020). In some contexts, the threat of public criticism can also act as a deterrent (Holley, 2012). Accordingly, there is precedent for courts ordering those found guilty of committing water-related offences to pay for an advertisement in a local paper or papers which publicizes the nature of the offence committed and the penalty imposed (Carmody and Slapp, 2020). Similarly, some jurisdictions record all successful prosecutions in a central, online register (NRAR, 2020).

Governments should also invest in community education programmes to ensure that water users understand their legal obligations, the purpose of extraction limits and the benefits associated with sustainable water management (NRAR, 2020). This may improve levels of voluntary compliance and reduce the need for agencies to undertake prosecutorial action.

Finally, it is important to reiterate that successfully detecting breaches of licensed extraction limits depends on accurate measurement of water at the relevant scale, be it individual or bulk (Holley, 2012). Put differently, offence provisions are unenforceable in the absence of this crucial data. The challenge of improving water metering in Asia has never been well addressed or sufficiently funded and remains a significant obstacle to sustainable water management in the region. Real-time monitoring via telemetry offers the opportunity to detect non-compliance almost immediately, and prevent further breaches (Abubakr, Haider and Zahoor, 2016) and to that extent should be considered where practicable to do so.

Well-resourced agencies

Even the best water laws will fail to achieve their objectives if they are not supported by well-resourced agencies that have a mandate to implement the law (Holley, 2012). By well- resourced, we mean agencies that have a sufficient number of suitably qualified staff with access to the necessary technology to carry out all aspects of water management, including those aspects that are particular to CBWM. These elements include (but are not limited to) water planning, monitoring water resource and ecosystem health and analyzing associated data, environmental flow management, remote sensing work, licensing, setting yearly water allocations and compliance and enforcement activities.

Compliance and enforcement activities should ideally be managed by an independent regulator that is separate from any other administrative units or agencies. This separation is necessary to avoid any possible conflict of interest, this being likely when the agency or administrative unit responsible for charging water users (that is, generating revenue) and is also responsible for regulating them (Matthews, 2017). However, sharing of information between administrative units and agencies should be encouraged where it will enhance the regulator's ability to enforce the law.

Compensation and adjustment packages

CBWM and associated extraction limits at the basin, catchment and bulk or individual water user scales will likely reduce the volume of water that is available for agricultural use. This will in turn result in some farmland being retired from irrigated agriculture. This requires the consideration and development of appropriate compensation and compliance mechanisms, ideally with input from the affected parties (World Bank, 2011a).

3.7 Additional enabling conditions for consumption-based water resource management

There is increasing recognition that effective water laws and water governance depend on the existence of enabling conditions, without which water agencies will not be adequately resourced, laws will not be properly implemented and overextraction of surface and groundwater will in all likelihood continue unabated. These conditions include most notably, high level political will and buy-in amongst key government agencies and stakeholders (Jiménez *et al.*, 2020).

Legitimate queries then arise as to how political will is created and how buy-in is secured amongst relevant parties. Although there is no single or simple answer to these vexing questions, it is important to acknowledge that these two issues (political will and stakeholder buy-in) are often intertwined. As noted by the United Nations Environment Programme (UNEP):

> *...the real challenge arises when these laws are implemented through regulations, policies, and actions that directly affect stakeholders' livelihoods, lands, properties and profits. Often environmental rule of law falters at this critical juncture because of a lack of political will to stand behind implementation of the law through clear regulations and policies that are enforced equitably and consistently.*
> (UNEP, 2019, p. 79)

Put differently, laws and policies which restrict resource use will invariably face opposition from individuals and corporate entities that depend on those resources for profit and in some instances, survival. This is particularly true in river and groundwater systems that are already overallocated. As noted in Section 3.6, it is vital to ensure that the rights and interests of small landholders who are vulnerable to being further marginalized by reductions in access to water are protected and enhanced, and any economic loss incurred as a consequence of policy changes is adequately compensated (noting that the cost associated with a compensatory scheme could further undermine political will).

Additionally, and given the links between political will and stakeholder buy-in, processes such as deliberative decision-making (DDM) and incentives for ecosystem services could help to increase stakeholder understanding of the vital role that healthy water sources play in human well-being. This could in turn translate into greater acceptance of extraction limits, environmental flows and CBWM as a means of addressing water scarcity.

3.7.1 Deliberative democracy

Increasingly, deliberative democracy (DDM) is being used by governments and other entities to work through highly complex and divisive policy issues, including in relation to water sharing and governance arrangements in Asia and North America (Dore, 2014; Scodanibbio, 2010). Although there is no single definition of DDM, the following description of deliberation arguably encapsulates its core elements:

> *Deliberation is debate and discussion aimed at producing reasonable, well-informed opinions in which participants are willing to revise preferences in light of discussion, new information, and claims made by fellow participants. Although consensus need not be the ultimate aim of deliberation, and participants are expected to pursue their interests, an overarching interest in the legitimacy of outcomes (understood as justification to all affected) ideally characterizes deliberation.*
> (Chambers, 2003, p. 309)

In this sense, DDM differs from traditional consultation and engagement frameworks which generally present stakeholders with a predetermined set of policy options rather than involving them in the decision-making process itself. The top–down nature of consultation can leave many stakeholders feeling alienated – and consequently inclined to resist (and possibly ignore) the final policy settings imposed by government. By way of contrast, DDM, which involves "...mutual justification, listening, respect, reflection, and openness to persuasion" (Dryzek *et al.*, 2019, p. 1145) , has been shown to improve the quality of debate, lead to "considered judgment" (Dryzek *et al.*, 2019, p. 1145) and augment stakeholder satisfaction with the eventual outcome. This is particularly true when DDM processes are overseen by a suitably qualified facilitator and participants are able to access expert evidence and testimony to support their deliberations.

It is important to note that DDM does not seek to impose a predetermined policy outcome on citizens. Accordingly, it is not a guaranteed pathway to generating stakeholder acceptance of CBWM. However, in contexts where CBWM (or other policies designed to address water scarcity) are politically unviable, it may help to improve stakeholder understanding of the risks associated with continued overextraction and the role that CBWM could play in restoring sustainable water use.

3.7.2 Ecosystem services

Ecosystem services are generated when ecosystems directly or indirectly help to meet human needs or maintain nature's intrinsic value. The benefits and associated values derived from ecosystem services can therefore be divided into three broad areas: ecological, sociocultural, and economic (noting that these can overlap) (Millennium Ecosystem Assessment, 2005). Categorization across these three broad domains highlights the complexity and subjectivity involved in valuing ecosystem services. This complexity is exacerbated by the fact that not all values are acknowledged or given sufficient weight by water managers, with non-material values (a vast array of spiritual and cultural uses, for example) most vulnerable to marginalization (Small, Munday and Durance, 2017).

Notwithstanding these complexities, the ecosystem services model can provide a useful framework for communicating the vital role that nature plays in supporting human survival and well-being (broadly defined). To that end, and within this anthropocentric context, the ecosystem services freshwater environments include but are not limited to drinking water, nutrition, a variety of cultural and spiritual uses, recreational uses, flood regulation and filtering of pollutants (Yeakley *et al.*, 2016; Ramsar, 2002). Highlighting these values can help to build greater awareness regarding sustainable and equitable water management practices, which is a necessary enabling condition for change.

The ecosystem service model also provides scope to consider the intrinsic value of nature (which is a subset of ecological values referred to above) (Small, Munday and Durance, 2017). This particular subcategory is particularly important given rising rates of species extinction, including in Asia. Some experts have suggested that the rate and extent of change to aquatic environments in the region may be greater than in any other part of the world. The causes of this degradation include overextraction, also pollution, flow regulation and impoundment of rivers, and the overharvesting of certain species (Dudgeon, 2000).

Again, building awareness in relation to these issues at different scales is arguably a precondition for generating policy and on-the-ground changes designed to improve the health of freshwater ecosystems.

3.7.3 Incentives for ecosystem services

Education regarding the ecosystem services provided by healthy rivers and aquifers may be usefully combined with incentives for farmers to transition to more sustainable practices. Incentives may range from reductions in land tax and other forms of tax, subsidies for non- polluting input costs, provision of training and materials required to adopt sustainable practices and so on (FAO, undated). Appropriately adapted incentives to restore ecosystem services degraded by overextraction could therefore form part of a broader set of water management policies within which CBWM sits. Indeed, incentives may help to increase stakeholder acceptance of CBWM as a tool to address water scarcity, thereby facilitating its implementation in relevant catchments.

Box 6. Case study B: Freshwater ecosystem services and incentives, Inle Lake, Myanmar

Inle Lake is the second largest lake in Myanmar. It is located between two mountain ranges in the middle of the Nyaungshwe Valley in Shan State and generates a diverse range of ecosystem services. From an ecological perspective, it is a biodiversity hotspot, providing habitat for 53 bird species and 36 fish species, including 16 endemic species, 4 threatened bird species, and 5 threatened mammal species.

Approximately 170 000 people inhabit the lake and its surrounds, with hydroponic cultivation known as floating gardens being a significant source of income for many. The lake also supports fishing, agriculture, and various tourist enterprises. Indeed, its picturesque setting, unique biodiversity and iconic floating gardens have helped to make it an ecotourism hub. It is also the main source of water for the Law Pi Ta hydroelectricity power plant, one of the major power plants in central Myanmar. The Lake also generates certain non-material ecosystem services, including spiritual enrichment, nature worship and aesthetic enjoyment (ICIMOD, 2017).

However, increased tourism together with a range of other factors including population growth, deforestation, agriculture and the floating gardens themselves have reduced the surface area of the lake and degraded the quality of its waters. Pollution caused by sedimentation, pesticides, fertilizers, sewerage and waste from a coal mine have had a particularly severe impact on the health of the lake and in turn on certain ecosystem services (Sidle, Ziegler and Vogler, 2007).

The Inle Lake Conservation and Restoration Project, which is a joint UNDP–Government of Myanmar–Government of Norway project, was developed in recognition of the fact that urgent action was required to reverse this degradation and restore these ecosystem services (UNDP, 2015). The project combined community education about ecosystem services with incentives to protect certain services. Incentives included provision of materials, training and the lowering of input costs for certain agricultural activities. The project report notes that the restoration project has not only "empowered communities in wanting new environmental conservation initiatives" (UNDP, 2015, p. 38), but also resulted in a greater awareness of the value of environmental services.

References

ICIMOD. 2017: A multi-dimensional assessment of ecosystems and ecosystem services at Inle Lake, Myanmar. ICIMOD Working Paper 2017/17. Nepal, International Centre for Integrated Mountain Development (ICIMOD).

Sidle, R.C., Ziegler, A.D., & Vogler, J.B. 2007. Contemporary changes in open water surface area of Lake Inle, Myanmar. Sustainability Science. 2, 55–65.

UNDP. 2015. Inle Lake conservation and rehabilitation: stories from Myanmar. Myanmar, United Nations Development Programme. (Also available at https://www.mm.undp.org/content/myanmar/en/home/library/environment_energy/inle-lake-conservation-and- rehabilitation--stories-from-myanmar.html).

3.8 Conclusions

CBWM is a highly technical system of water management that requires a certain set of legal and governance mechanisms to be in place if it is to be properly implemented and deliver real water savings. This renders it ill-suited to certain contexts, including countries dominated by multiple, intersecting legal systems and a high level of uncertainty and conflict regarding land ownership and associated water use. However, countries or provinces with an overarching legal and governance framework that appears prima facie capable of being adapted to integrate CBWM may wish to consider rolling out a pilot project to test its feasibility in a given location (on condition that such pilots do not depend exclusively on external funding and expertise, which is ultimately unsustainable). The use of DDM may help to determine if local water users and other affected stakeholders consider it a viable means of combatting water scarcity and if they do, may increase buy-in and levels of voluntary compliance.

Chapter 4. Technical considerations in implementing consumption- based water management

Consumption-based water management (CBWM) relies on the estimation of spatially and temporally variable crop evapotranspiration (ETa) using freely available satellite data and a variety of well-researched techniques that have reached practical and routine application in favourable conditions and with good calibration.

The process of CBWM is focused on agriculture as the dominant diverter and consumer of water. It thus focuses on the delivery of water from aquifers, dams and river diversions and the monitoring of actual consumption by crops in different farming systems across the landscape.

4.1 The process of consumption-based water management

Management of water use implies a process of **planning or forecasting** water needs, **delivering** agreed volumes to users, and **monitoring** actual use. Where actual use exceeds planned or sanctioned use (a quota), some form of correction is needed to reduce overuse in the future and, possibly, to penalize offenders as a means of disincentivizing poor compliance. Management of consumptive use follows the same principles but incorporates more steps (Figure 10).

In market-based economies, water demand must be forecast and communicated, as top- down plans are unlikely to be adhered to unless very well incentivized and managed. The techniques used to plan or **forecast** crop water demand include the **estimation** of cropped areas by commodity and location and their **potential** water use under average or expected climatic conditions. It is possible to build some flexibility in water allocation procedures that takes account of interannual variability in supply and advises farmers in advance of estimated water availability as a proportion of their individual or bulk entitlements (“announced allocation” in Australia). It is then up to individual farmers to decide how best to use the allocation they are likely to receive in the coming water year.

Consumptive use can be predicted from climate measurements on the ground (Allen, Raes and Smith, 1998 and actual ET (ET_a) can be directly monitored using remote sensing (Actual soil moisture and crop conditions may vary dramatically in practice from those assumed in the prediction of crop water demand. Soil–water balance models (more correctly crop–soil–water balance) models are used in the Hai River Basin to predict crop water demands for representative areas, using average or other climate conditions over a year.

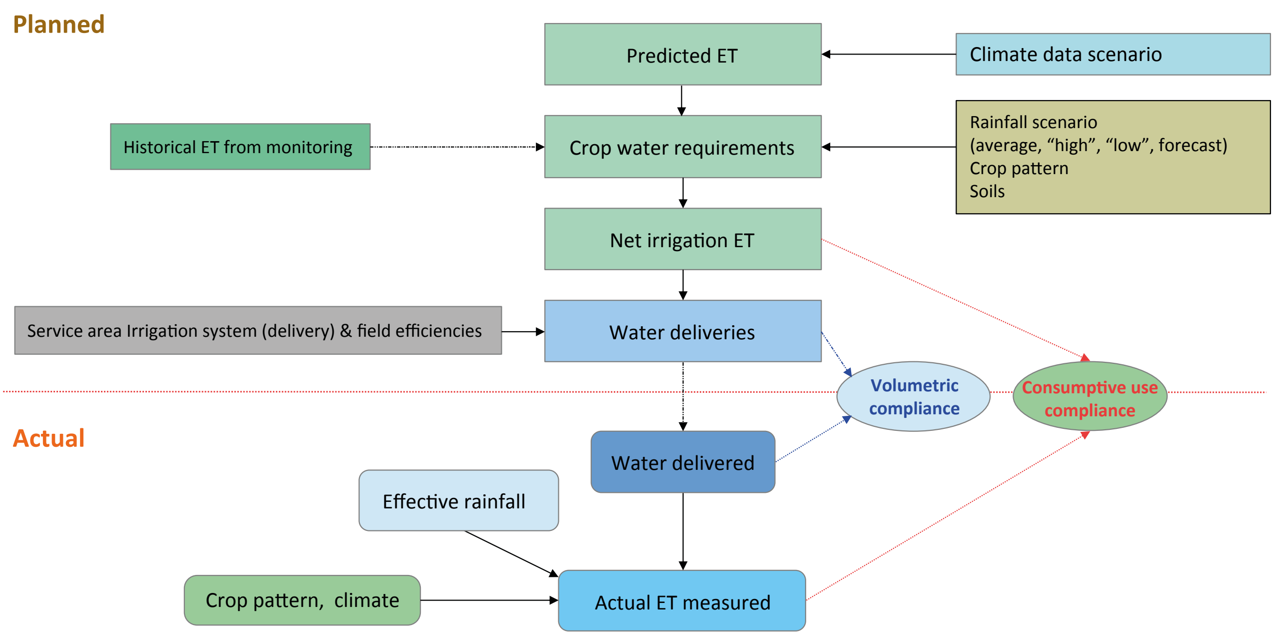


Figure 10 Conceptual overview of the management of consumptive use

Source: Authors’ own elaboration.

Consumptive use in the estern United States of America has traditionally been estimated indirectly by water balance, where cumulative seepage and leakage from channels and pipes and field scale water losses associated with different water application technologies and their management are deducted from diversions from rivers and groundwater (**Chapter 2**). This approach relies on gathering flow data, crop area and crop type and information on different irrigation technologies in use. Because it is complex, indirect and relies on many assumptions, there are many possibilities for small errors to accumulate, such as in calculating the proportion of water delivered that is actually consumed, which may be calculated from assumed uniformity of irrigation and application efficiencies.

Conventionally, irrigation water is delivered from surface diversions or pumped from aquifers through a network of channels or pipes to users' fields. **Flows** can be measured from a source, through intermediate levels of the delivery system, to farmers' fields. In much of Asia, flows may only be reliably measured at the offtakes of large-scale and medium-scale irrigation systems and are rarely measured in small ones or at well heads. Australia is highly unusual in that flows delivered at each farm outlet in irrigation districts are measured continuously and also throughout the delivery network (Turral and Wood, 2013). An irrigated farm in Australia is roughly equal in size to the area managed by a water user association in a large Asian irrigation system and may be bigger than an entire small surface irrigation scheme.

The **actual delivery** of water can only be quantified in terms of flow rate or cumulative volume. **ET quotas issued to users must therefore be converted into flows or volumes and include an increment required to ensure delivery of the net amount at the point of use. In other words, an ET quota must be converted into an irrigation quota.**

In northern China, groundwater abstraction is increasingly being routinely measured, under conventional management and in pilot projects for managing consumptive use (ET). Meters are installed at the well head and smart cards are used by farmers to book irrigation time and start and stop pumping. The smart card technology allows water deliveries to individual farmers to be recorded on a computer at the Water User Association office and thus keep track of total delivery to each user for comparison with monitored consumption, determined from remote sensing.

There are two fundamental reasons why the quantum of ET_a is significantly different from the amount of water diverted:

- In dry conditions without rainfall, ET_a is less than the volume delivered because of water losses in transmission and because of non-uniform application in the field. Predicted demand includes an allowable or desirable amount of loss (return flow) at system and field levels but, in practice, values are often optimistic and set at the original design values rather than actual measured ones. Where infrastructure is in bad condition, the proportion of water consumed compared to that diverted at source may be less than 30 percent.
- In semi-humid conditions, where irrigation is needed to ensure crop production, but rainfall also contributes to a significant portion of ETa, the amount of **effective rainfall** must be included when establishing the irrigation quota volume for delivery, and when assessing quota compliance, which is relative to the ET quota for irrigation supply, not from irrigation plus rainfall.

In well-managed irrigation systems, such as those with arranged demand and on demand service, water deliveries can be adjusted to avoid irrigating when, or soon after, rain has fallen. However, at the start of a water year, neither farmers nor service providers know how much rain will fall and when. Farmers need to know the minimum amount of water that will be available to them at the start of a season to make appropriate planting decisions. Thus, a minimum announced quota needs to be determined at the start of the season even though it may be increased as the season progresses, when dams fill or river flows are greater than predicted. It has been suggested that quotas could be continually varied as the season unfolds, but the administrative transaction costs, and lack of certainty at the start of a season make this an impractical task.

Conceptually, it is possible to manage ETa at large scales through strategic planning of land use (forest, rangeland, rainfed agriculture, waterbodies etc.), but in practice this is both challenging and a very long-term activity that is hard to regulate in most political– administrative settings.

4.2 Remote sensing, agriculture and consumptive use

Remote sensing (RS) and geographic information systems (GIS) have become basic tools for natural resources management thanks to continuing research and rapid adoption over the period from 1980 to 2010 (World Bank, 2019; ICID, 2000). Since then, there has been a significant increase in the number of satellite platforms and the range of sensors deployed and so the range of applications has grown accordingly. When observable from space, both the temporal and spatial variability of natural processes at, and beneath, the earth's surface can be monitored effectively. RS observations are also used to interpolate data captured at ground level by stations that record continuously, with good precision, but which are sparsely distributed across the landscape.

A major benefit of remote sensing is that it is spatially explicit, and parameters such as ET_a and rainfall can be determined pixel by pixel over large areas, incorporating a great deal of variability that is not represented when using indirect (water balance) methods.

Remote sensing is widely used in many aspects of natural resources management with particular attention paid to weather, agriculture, ecosystems and drought. Uses of RS in relation to agriculture and water include:

- land use mapping – crop and vegetation identification; irrigated area mapping and delineation; and crop productivity, yield and net primary productivity of vegetation, including forests;
- landforms and topography – digital elevation models, used for base maps, simulation modelling and to correct radiometric data for RS analysis; slope hazard models; and delineation of catchments, flood plains;
- snow hydrology; yield; climate change impacts;
- some aspects of river monitoring: flow/no flow;
- wetland areas (and extent); wetland condition and health;
- climate change monitoring: surface temperatures (land and sea): rainfall distribution and intensity;
- drought – warning (evaporation index and others), monitoring, extent, duration;
- flood (extent, duration);
- storm and cyclone tracking;
- evapotranspiration and water use;
- dam storage (extent); and
- water balance (rainfall and evapotranspiration).

Although ET measurement is only one strand of remote sensing science, it incorporates techniques originally developed for other purposes, such as vegetation monitoring, soil moisture assessment and land surface temperature detection.

4.2.1 Basic concepts in remote sensing

Imaging sensors on satellites observe reflected radiation from the earth's surface in **optical** and **microwave** portions of the electromagnetic spectrum. Optical sensors measure reflected electromagnetic radiation across visible and near infrared wavebands, through shortwave infrared and thermal infrared wavebands. **Colour composite images** can be made by combining red, green and blue wavebands in the visual spectrum and can be substituted with various infrared information to create three-band **false-colour composite images**, all of which have recognizable photographic characteristics.

Cloud cover prevents reflected visual and infrared radiation from reaching satellites, which can sometimes severely limit practical application, for example when cloud cover is continuous throughout a season or even most of the year. Hanoi, in humid, subtropical Viet Nam, experiences only 72 cloud free days per year on average.

Microwave instruments can penetrate cloud cover and can also record at night. They include passive instruments, which are generally coarse scale and are used in meteorological applications. Increasingly, there are active synthetic aperture radar platforms in space that can provide high resolution topographical information (the well-known Shuttle Radar Topography Mission global digital elevation model, can map flooding in real time (during emergencies) and can map rice areas and dynamics in humid tropical conditions. Passive microwave sensors are used to map soil moisture and these have improved the performance of global climate models through better initialization. Synthetic aperture radar has been used successfully in algorithms to estimate.

From a practical perspective, three aspects of satellite information are fundamental: **timeliness, frequency and spatial resolution** (Jackson, 1984). The main importance of **spatial resolution** is in terms of what a pixel represents on the ground.

In very high-resolution imagery geometric detail can be observed (for example 1 m to 2 m imagery from commercial satellites, commonly seen in Google Earth images, that clearly shows houses and individual cars on the street). Also, in very high-resolution imagery, the variability of land surface **within** one pixel is small. In contrast, the area sampled from geostationary satellites, such as METEOSAT, is 4 km x 4 km at the highest resolution and averages a wide range of land surface conditions within each pixel. Acceptable resolution might be 1 km (MODIS) for river basin and catchment scale analysis of land and water use but must be finer at irrigation system level (30 m, Landsat) with additional improvements in resolution needed to define field boundaries and infrastructure layout (15 m pan ("black and white") imagery, or better).

The spatial resolution of microwave imagery cannot be interpreted in the same way as for optical data. In the case of synthetic aperture radar, the reflected signals from neighbouring physical pixels interfere with each other and so moving window averaging is used to determine a representative value for a larger area (say a 3 x 3-pixel box). An advantage of active microwave sensors is that they can operate at night as well as in all weathers and cloud conditions.

The **frequency** of satellite data collection is determined by its orbit. Geostationary satellites, such those used for meteorological monitoring (GOES, Meteostat, GMS), can collect data every 15 minutes or so ("continuously"), but only sample a defined footprint on earth: GOES covers the United States of America and the Americas, Meteostat covers Europe and GMS, and others cover Asia and the Pacific. Polar orbiting satellites orbit the earth daily and may sample all areas of the globe in 24 hours, but at medium-scale resolution varying from 250 m to more than 1 000 m pixels (Visible and Infrared Radiometer (VIRR), Moderate Resolution Imagery Spectroradiometer (MODIS), Advanced Very-High-Resolution Radiometer (AVHRR)). In the semi-humid tropics, high frequency overpass is desirable to increase the chance of obtaining a clear image that is free from cloud cover so that an acceptable time series can be created over both wet and dry seasons.

Timeliness of image capture is both related to local time of day and to the frequency of image capture. Optical data cannot be captured at night and polar orbiting satellites are sun-synchronous, passing over any point on the globe within a few hours of local midday. What are normally considered redundant (night-time orbit) overpasses can yield additional information from thermal sensors, although there are complications in determining atmospheric conditions needed to process signals since these rely on optical reflectance.

In crude terms, spatial and temporal resolution are inversely related. Coarser resolution sensors such as MODIS (250 m to 1 000 m pixels) observe the same path every day, whereas higher resolution sensors (such as Landsat and Sentinel) have a narrower field of view (swath width),[6] and their orbits shift daily over the repeat-pass-interval, which is the interval between consecutive overpasses at any point (16 days for Landsat).

Continuity in data collection is determined by the trade-offs between spatial resolution and temporal frequency. If there is **cloud** present in an image (at 16 days) but conditions are clear at the next overpass (32 days), the effective temporal resolution of optical data decreases by a factor of two. Conversely, the interval between sampling any point on the ground can be halved if there are two satellites with the same capability orbiting in tandem (such as LS7 and LS8 and Sentinels 2A and 2B). Continuity is crucial to earth observation applications so that long time series are available, both for historical analysis and in respect of climate change science. The continuity of high-resolution thermal imaging is an important question in RS-ET estimation. The only relatively high-resolution (60 m and 100 m) thermal infrared data generally available is provided by Landsat 7 and Landsat 8 respectively, but Landsat 7 has a scan line corrector problem that diminishes spatial coverage. Landsat 7 will end its natural life soon and be replaced by Landsat 9 in 2021 to provide Landsat continuity. There is better thermal data continuity from VIRR which extends the data record from AVHRR and MODIS (from 1981 to the present day).

6 Swath width is the distance perpendicular to the flight path that is sensed on the earth's surface. Coarser sensors have a wider angle of view, larger pixels and therefore have large swath widths of up to hundreds of kilometres and which partially overlap. Fine resolution sensors have a narrow angle of view and narrow swath widths, which may not overlap. Even higher resolution sensors have very narrow angles of view, requiring they be pointed at specific targets and times for data acquisition, which is useful in science application, but less useful in routine earth observation and monitoring.

An image processing technique that is increasingly used to improve temporal resolution is to fuse more frequently captured data, such as daily medium spatial resolution imagery (MODIS 250 m and 500 m visible and near infrared data, and 1 000 m thermal infrared data) with less frequent, higher resolution imagery such as Landsat (30 m visible and near infrared data, 100 m thermal infrared data) and Sentinel (10 m visible and near infrared data).

Thermal **fusion** of high-resolution data, such as Sentinel visible and near infrared data with the National Aeronautics and Space Administration's (NASA) ECOsystem Spaceborne Thermal Radiometry Experiment on Space Station (ECOSTRESS), Sentinel 3 and MODIS/VIRR thermal infrared data, is one emerging route to improving the availability of thermal information at spatial scales needed for ET assessment. Thermal sharpening of MODIS/VIRR data with Landsat thermal infrared is also a way of improving thermal band resolution, leading to new products such as 375 m thermal grids from VIRR.

Practical use of RS-ET in CBWM also requires contextual information, particularly on the spatial distribution and quantity of rainfall to attribute ET from irrigation water and effective rainfall. When looking at compliance with quotas, remote sensing can also be used to identify land cover, land parcels and their boundaries.

4.3 Data availability, processing and ease of use

There has been rapid development of a number of platforms such as FAO's Water Productivity Open-access Portal (WaPOR) and Earth Engine Evapotranspiration Flux (EEFlux) that either provide ET_a data or provide an automated calculation of ET using data and algorithms of choice (e.g., OpenET). In the future, users will not need to be as literate in remote sensing science nor as knowledgeable of the algorithms used to calculate ET_a.

In the last five years, both the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have made the majority of their data available for free in the public domain and this has spurred the development of portals either that provide or simplify the calculation of ETa. Although much data is free, most of the methods to calculate ET are not open source and although they can be used for free, they cannot be further developed by the water community directly.

WaPOR is provided as a web-based tool by FAO, using energy balance algorithms developed in Europe (ET Look) and data from NASA and ESA, including high-frequency, high-resolution Sentinel data. At the moment, WaPOR can provide data for the Near East and North Africa (NENA) and sub-Saharan Africa and users can select locations, resolutions, and time spans on an interactive map. WaPOR is being extended to Asia, with some data available for Sri Lanka.

The limiting factor for the "instant" use of such products is the effective accuracy and the availability of data to either validate or calibrate the results and give assurance of accuracy to users, especially if RS-ET data will be used for legal compliance. OpenET (sponsored by multiple agencies and partners) will, in the fullness of time, provide ETa data through a choice of data and processing methods for much of the globe. In its current phase, OpenET is focused on North America, where calibration and validation have been and can continue to be carried out. The development of EEFLux has led the way in this regard with extensive calibration and validation work for the METRIC algorithm across the United States of America.

For practical benefit in Asia, users more than ever require sufficient bandwidth and internet speed to be able to download RS-ET and other products. Data storage requirements, even with cloud services, are not trivial and adequate archives will be important and costly.

Although free and widespread ETa data provision is tantalizingly close, it is important to have advisory and technical staff who understand the detail, background, computation methods, data, limitations and accuracies involved when combined in a water allocation and management system that accounts for consumptive use. In the current situation it is very necessary to acquire and use that expertise.

4.4 Measurement of actual evapotranspiration using remote sensing

Remote sensing to estimate ET is considered a mature science and is sufficiently accurate in arid and semi-arid conditions (+- 10 percent absolute error), making it very appropriate for assessing irrigation water use in dry environments (FAO, 2019). Many different approaches have been developed over the past 30 years and the field continues to be very dynamic.

With good calibration and validation, estimation of RS-ET can be as accurate in humid environments, especially in conjunction with land use mapping to distinguish the source of consumptive use – whether from irrigation, rainfed agriculture, forestry or other use (IWHR, 2019; Wu, 2012).

Operational constraints remain in two key areas, namely cloud cover limitations on sufficient imagery to estimate ET over full seasons and years in humid and seasonally wet conditions, and the need for effective validation and possibly recalibration in "new" conditions (Steduto, 2019; Xiong *et al.*, 2011).

There are two broad groups of methods to estimate ET. The first includes a range of **empirical techniques** that use observed vegetation characteristics to convert ground-based meteorological estimates of reference ETo into actual ET_a across a landscape. The second group comprise **energy balance models** that represent the conversion of solar radiation into sensible heat (at the air and land surfaces) and latent heat (in evaporation and transpiration of water).

Empirical methods always require calibration against ground data and require contextual information on what types of vegetation are present for characteristic landscapes and agro- climatic conditions. They use visible and near-infrared data, which are now available at high spatial resolution (2 m to 10 m) to calculate **vegetation indices** (normalization difference vegetation index, enhanced vegetation index etc.) that convert reference ET (measured on the ground) to actual ET. To date, most commercial services calculating ET for irrigation scheduling purposes use empirical methods, as data is available in a timely fashion at farm- scale resolution and is relatively quick and easy to process (Calera *et al.*, 2017)

There are two subcategories of **energy balance methods**: **single source models**, which consider the ground surface as "one big leaf"; **and two source models**) that estimate evaporation from the soil and transpiration from vegetation separately.

Energy balance approaches are complex but more generally applicable, require intensive computation and can estimate ET without needing to know the details of vegetation and land cover. Nevertheless, land cover is needed as contextual information for ET **management**. In addition to using **visible and near infrared** information to calculate vegetation parameters in the energy balance, estimates of land surface temperatures from **thermal infrared** imagery are required.

Estimates of the latent heat flux can only made at the time the satellite passes the target area. Therefore, the latent heat flux must be converted to a daily value of evapotranspiration (in mm of water). Happily, there is good experimental evidence that ET is strongly correlated to evaporative fraction (the proportion of ET_a to ET_o), which can be recorded at a nearby meteorological station on the ground. Thus, ground-based estimates of daily evaporative fraction are used to determine daily ET_a. Recent science has improved this conversion using additional information on the boundary layer height and the cloud cover pattern over the site during the rest of the day (Liu *et al.* 2011).

Similarly, the ET on each day between successive image capture must be interpolated, and this is again achieved using evaporative fraction on the ground (and boundary layer height measured from geostationary satellites).

Single source energy balance models (SEBAL, METRIC) work well in irrigated conditions, where there is relatively uniform vegetation cover and high levels of evaporation.

- Thermal sensors are less common and have coarser resolution than visible and near infrared / shortwave infrared instruments. The main sources of thermal data are Landsat 7 (60 m) and Landsat 8/9 at 100 m at 16-day repeat pass intervals; Sentinel 3 (300 m resolution at 27-day repeat pass interval) and AVHRR/MODIS/VIRR at 1 000 m to 370 m on a daily basis.
- Thermal data at 1 000 m resolution is too coarse for application in agricultural and irrigation management (Allen, Tasumi and Trezza, 2006) but is optimal at catchment and river basin scale (Senay *et al.*, 2011; Wu *et al.*, 2013).

- Higher resolution Landsat data is the effective standard for agricultural applications, although thermal data must still be downscaled to 30 m and 15 m resolution if ET is to be measured at field scale in countries with large farms (and large fields). Identifying farm level ET in many developing countries, where plot sizes are less than 10 m x 10 m, remains a challenge, but is less important than collective water use at WUA scale.

In some conditions, land use may be quite varied within an irrigation system, with dry and fallow lands and upland areas that are not supplied with water. Orchards and other widely spaced row crops also have a large soil area relative to the vegetated area. At river basin scale, where there are high proportions of non-vegetated land and vegetation that is not well watered, single source energy balances do not estimate ET reliably and other approaches that effectively separate soil and vegetative fluxes and work well in water limited situations (rainfed agriculture, rangelands, and forestry).

Parallel-source models such as surface energy balance system (SEBS) make use of the same physics as single source energy balance models with a modification of the Penman–Monteith energy balance model used to partition soil (evaporation) and vegetative (transpiration) components of water use. Surface energy balance system and its derivatives are used for river basin scale estimation using 1 km (MODIS/AVHRR/VIRR) data. Prior knowledge of land cover conditions is important for continental scale application, where many different biomes and agro-ecological zones are observed. The MOD16 Global ET product from NASA specifies a biome type for each pixel to improve calibration values and performance.

Two source energy balance models are intrinsically better set up to measure ET from mixed land surfaces (Norman, Kustas and Humes, 1995). The first practical large scale two source RS-ET model (ALEXI) used thermal data from geostationary satellites with a 4 km x 4 km pixel resolution (Anderson *et al.*, 1997), which is rather coarse for water resources, river basin and catchment management applications. A downscaled development that uses multiple sources of data with different temporal and spatial resolutions (disALEXI), has been extensively and satisfactorily tested across the contiguous United States of America (Anderson *et al.*, 2011). ALEXI–disALEXI has been refined into a multi-sensor observation system that can provide 30 m resolution estimates of ETa on a daily basis with a 9 percent to 25 percent error compared to flux tower measurements across different land uses in the United States of America (Anderson *et al.*, 2007; Camilleri *et al.*, 2013; and Camilleri *et al.*, 2014).

None of the energy balance models do a very good job of estimating evaporation from bare water surfaces, as they are designed to estimate water use from vegetated surfaces that have resistance to water vapour transport. Some empirical models, such as the CSIRO MODIS Resistance-based Scaling EvapoTranspiration (CMRSET) model, have been shown to estimate both mixed surfaces and bare water surfaces well (Guerschmann *et al.*, 2008).

Both energy balance and empirical models can give misleading information over built-up areas, particularly cities, which can be masked out of the analysis even if in practice there will be some consumptive used from gardens, parks and other vegetation within an urban area.

4.5 Accuracy, calibration and validation

Potential users of RS-ET are invariably interested in its accuracy. Of course, the level of accuracy required will depend on the desired purpose of measurement. For example, a regulator who wishes to use it to monitor irrigation consumptive use with a view to prosecuting those who have exceeded their quota would require a relatively high level of accuracy in order to satisfy the criminal burden of proof. By way of contrast, a water manager wishing to use it to assess basin-scale diversions may find a 20 percent margin of error acceptable insofar as this would be of a similar magnitude to the error in the measurement of precipitation. Errors greater than 20 percent are unlikely to be practically acceptable for most applications.

Various reviews of energy balance methods have found 10 percent to 20 percent errors, compared to 15 percent to 40 percent for procedures based on vegetation indices (Allen *et al.*, 2011), and falling to as little as ± 5 percent for single and two source energy balance models in well-calibrated conditions (Karimi and Bastiaanssen, 2015). Evaluations by potential users in Texas indicated relative errors of up to 28 percent (Evett *et al.*, 2012). Validation exercises across eight eco-regional sites in China, revealed errors ranging from as low as 6 percent of annual basin ET to about 27 percent for daily ET estimates at a site near Beijing and generally between 15 percent to 18 percent compared to a range of reference methods (Chen, 2019).

All methods of estimating ET from remote sensing require **calibration** because the algorithms employed include assumptions and empirical relationships needed for their solution (Steduto, 2019). Empirical methods require calibration in each new setting, especially with different types of vegetation, crops, and climate conditions. Physically-based energy balance models may only require **validation** – a check that a calibrated universal model actually works effectively in new and different agro-climatic contexts. Validation will be required in countries and agro-climatic zones where no testing has been done before. If the results from validation exercises are unsatisfactory, then **recalibration** may be required, assuming the potential value of doing so is worthwhile.

Greater accuracy is needed at higher resolutions, such as field and farm scale, compared to river basin scale. Unfortunately, the opposite is true in practice: the lowest absolute and relative errors are seen in comparisons of RS-ET and annual water balance at river basin scale (~5 percent) (Xiong *et al.*, 2011) and the highest ones measured at research plot scale (~20 percent +) (Chen, 2019). This experience is widely reflected in the literature from different countries.

A significant challenge for the calibration of RS-ET data is that ground-based reference ET methods have similar levels of error, and in general represent only a small part of the variability captured within one remote sensing image.

The statistical tests employed to compare RS and ground-based ET values therefore assume equal levels of uncertainty. The majority of comparisons and error metrics are derived from linear regression of modelled (RS) on observed (ground station reference) estimates of ET_a (mm hr^{-1} or mm d^{-1}) and energy balance components (Wm^{-2}).

It is generally useful to know absolute and relative errors in relation to the range of commonly observed values and their variability. An absolute error of say 0.5 mmd^{-1} over a whole river basin with an average ET of 1.5-2 mmd^{-1} (as in the Murray–Darling Basin) is not very encouraging (25 percent to 33 percent), but relative to a peak daily irrigated ET of 10 mm, it is quite acceptable (5 percent).

Precipitation needs to be measured to predict crop and vegetation water requirements, and to partition ET_a from irrigated crops into the fraction sourced from rainfall and the fraction sourced from irrigation. It is also needed for any water balance calibration and validation work. ETa between successful satellite overpasses is interpolated using assumed consistency in the evaporative fraction or a relationship between evaporative fraction and other observable factors, such as boundary layer height. It is also interpolated over cloud cover days. In both cases, rainfall at some point during the period will result in higher ET_a in practice than would be predicted from the interpolation scheme.

RS-ET methods are currently best suited to arid and semi-arid environments with low cloud cover. They can work well in semi-humid conditions, such as the Hai Basin, providing cloud cover does not inhibit sufficient data collection. Accurate and effective monitoring in the seasonally humid tropics, even in the dry season, is not yet a good bet although new options are emerging. This argues for careful assessment of the feasibility of practical RS-ET monitoring at an early stage.

4.6 Assessing the feasibility of using remotely sensed-evapotranspiration to undertake consumption-based water-management

Analysis undertaken for Texas (Caldwell *et al.*, 2017) include an assessment of cloud cover probability which revealed that even if there were two Landsat platforms effectively sampling every eight days about half the state would have less than a 20 percent chance of capturing one image every 32 days (Caldwell *et al.*, 2017).

Here, the feasibility assessment is shown in a process diagram (Figure 11). The early steps test whether it is even worth proceeding to validation if the costs of a validation programme are unattractive. Although not explicitly stated, test conditions at each stage include an assessment of costs that will be incurred.

The process begins by examining whether there is enough data available to validate and, if necessary, recalibrate any RS-ET method under consideration. If it is insufficient, the cost of equipping and staffing new sites should be considered. This phase would include and assessment of rainfall data over the target areas, and the ability to determine net ET from delivered water (Figure 11). It would also consider the option of using any global data sets that might substitute for locally collected meteorological data.

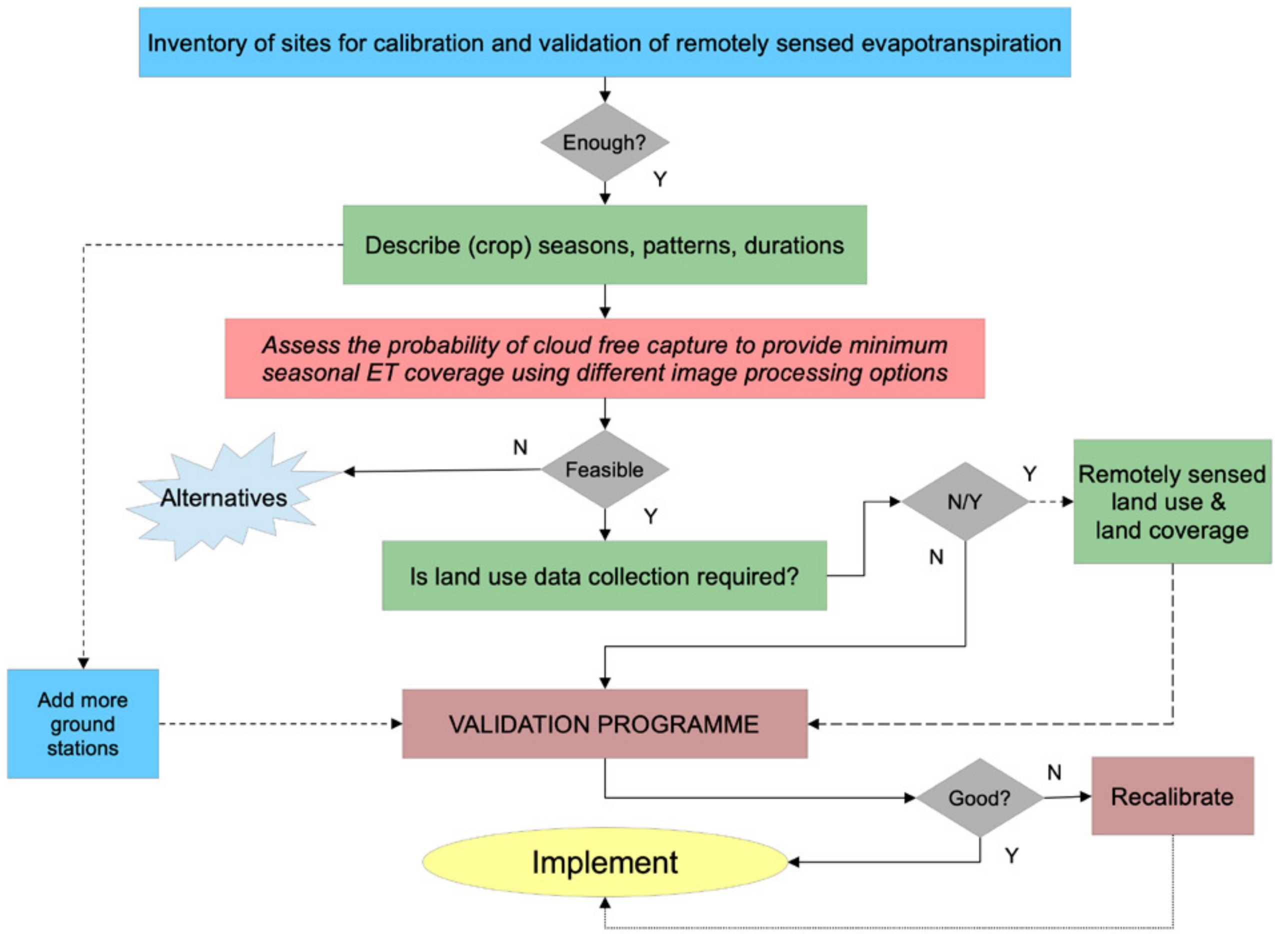


Figure 11 Steps in a feasibility assessment to apply RS-ET for consumption-based water management

Source: Authors' own elaboration.

The timing, duration and seasonality of crop seasons that require irrigation is a step to ascertaining whether sufficient data can be obtained from remote sensing over the target area for the full season. The analysis outlined by Caldwell *et al.*, (2017) could be used to produce cloud cover probability maps. If cloud cover conditions will not permit effective remotely sensed data capture, or if the additional cost of new ground truth is high relative to expected benefits, then alternative measures to control consumptive use will be needed.

Land use data is required to be able to ascribe water use to different specific areas and crops, irrigation systems, or groundwater use areas. If cropping data is insufficient to implement consumption-based management, a new programme of collection will be required, and if cloud permits it could be done largely by remote sensing with a well- designed ground truth campaign. This step does not prevent validation, since if crop data collection is worthwhile it is needed for routine implementation of CBWM.

A pilot exercise might give a better idea of the costs of full-scale (basin-wide) crop monitoring and allow a preliminary analysis of crop water use.

Finally, if the validation reveals poor performance in the estimation of RS-ET, recalibration is possible, probably using the validation data already collected. If calibration results are good, then a realistic assessment of the costs, staffing and training requirements is required before funds can be sought for the implementation of a CBWM programme.

It should be noted that this feasibility assessment only investigates the costs of the technical component of monitoring ET with remote sensing. It says nothing about the administrative feasibility, the capacity constraints and the legal requirements of rolling out a pilot CBWM programme, even less a full-scale programme at basin or national scale.

4.7 From evapotranspiration measurement to evapotranspiration management

Consumption-based water management sits at the apex of water resource management processes and requires many antecedent activities and innovations to be in place (Figure 12).

- Where resource use is significantly less than sustainable water availability, it is rare that much quantitative water management is practiced. It is of course very desirable to measure water use to be able to manage it effectively, even in the early stages of development. In the development phase, flows must be measured to deliver the right amount of water to users, but it may not be useful to measure consumptive water use. As technology progresses, it is likely that the costs of monitoring water use with remote sensing will be cheaper than measuring flows and therefore a rational, least-cost water management system would incorporate both flow measurement and ET monitoring. As noted at the beginning of this chapter, water, not ET, is delivered to users and so measurement of flows will always be important.
- As water use approaches a sustainable limit, there is an ever-increasing need to formally allocate water to different users, who may (in certain locations, seasons and years) be in competition for full satisfaction of their needs. At this point it becomes essential to set a cap on water use, and preferably this should be done before such a difficult situation is reached.
- Once the sustainable limit has been exceeded, whether or not there is a formal cap, reallocation will be required and will result in both winners (usually high value water uses and users) and losers. To date, the environment has been the immediate loser, with knock on impacts on the whole of society. In the longer term, the most likely losers will be agricultural water users since they consume the most water. Both allocation and reallocation options and actions depend heavily on a complex range of factors including other sectoral policies, stakeholder perceptions and power, institutional frameworks, laws and regulations, and politics.
- Once a formal cap is in place, consumption-based water management can start but water use will only be restrained if compliance is achieved and monitoring water use is sufficiently accurate.

Even if consumptive water management is being practiced in the agriculture and environment sectors, water managers will need separate systems to account, manage and monitor non-consumptive use in other sectors, which may in fact be partially consumptive, but is not amenable to observation by remote sensing, for example, water quality degradation in urban and industrial water use

4.8 Managing evapotranspiration quotas

Simplistically, the chain of quota setting proceeds from a cap on water use and the priorities accorded to high value, environmental and socially important uses. The residual amount can be distributed to agricultural water users through successive tiers of quotas at subsidiary hydrographic and administrative jurisdictions, down to water user groups or individuals.

A linear, top-down process is unlikely to be a good option in most political administrative situations, where there are established legal and de facto water use rights and multiple stakeholders to be consulted and engaged.

In most countries in Asia there is no formal water allocation process, little water accounting and, outside China, no basin-level caps on water use. This implies that the whole process sketched in Figure 12 needs to be completed step by step. Establishing effective water accounting and allocation processes are already long-term and demanding tasks.

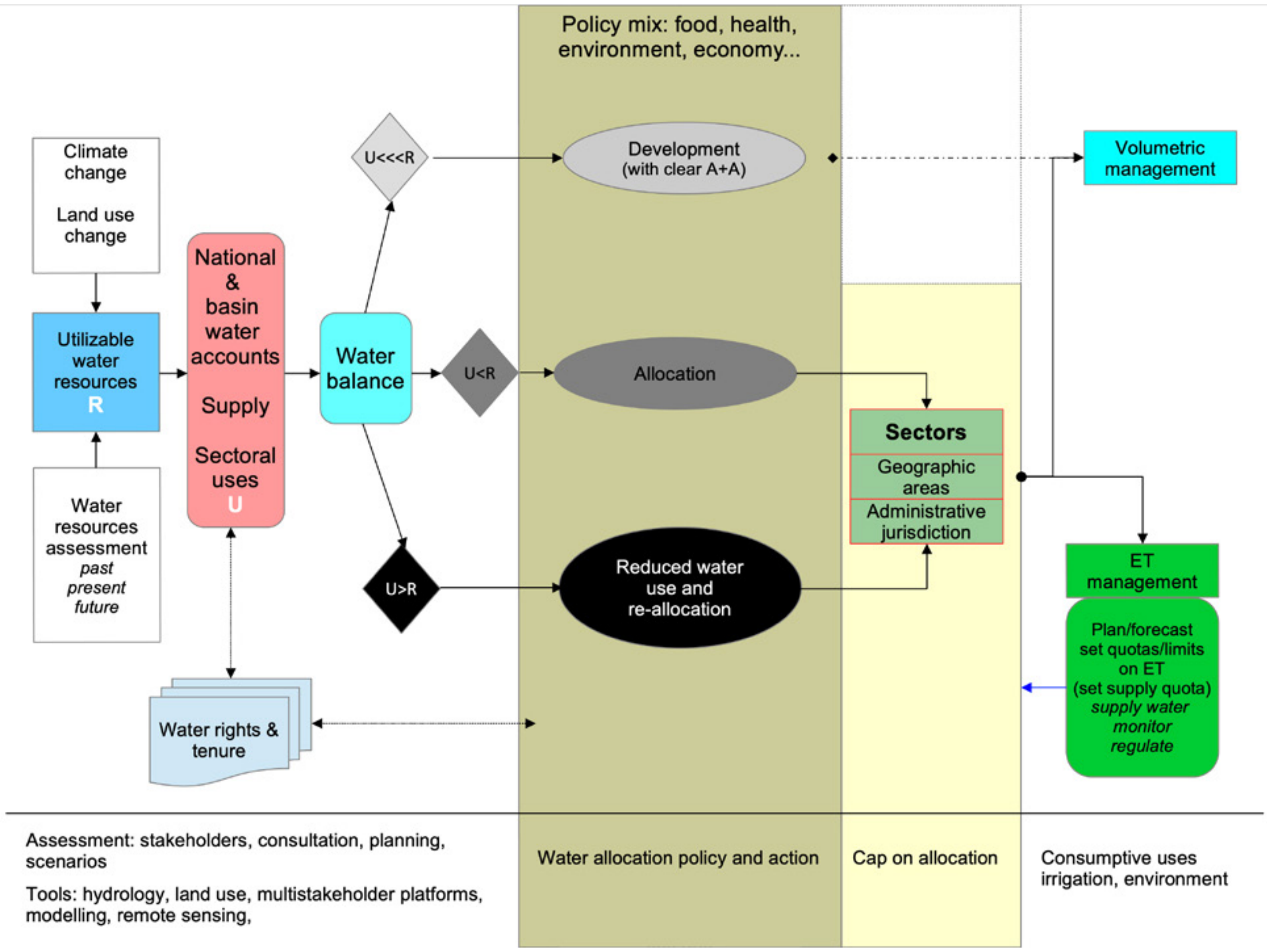


Figure 12 Where management of consumptive use fits in different contexts of water management

Source: Authors' own elaboration.

There may be opportunities to introduce ET monitoring and even quota-based management for particularly high-pressure situations, such as managing severe groundwater overdraft. The prime focus of consumption-based water management in China is on stabilizing groundwater tables, where overuse by agriculture, industry and cities is causing significant externalities.

Since ET cannot be directly allocated, flows must be managed and consumption-based water management requires intensive volumetric measurement to ensure that individual and bulk quotas are delivered to users. In fact, the data management demands of ET management are very high, as they require:

- RS-data management for monitoring;
- meteorological data for RS data processing and to determine the contribution of rainfall to gross ET and allow calculation of net ET from diverted water resources;
- volumetric measurement and control to deliver precise amounts of water to users that matches the precision of RS-ET assessment; and
- contextual information on crop patterns to attribute water use.

The administrative requirements of CBWM are proportional to the granularity of quota specification. If quotas are applied to individual farmers, the administrative load is massive, especially if ET-based water rights are allocated, as they are (annually) in pilot projects in the Hai River Basin in China. If quotas are specified at a larger scale – water user association or a whole irrigation system – the administrative burden declines but is still daunting.

The business of compliance is likely to be complex and will fail if transaction costs are high. Compliance in Asia is unlikely to be achieved by sanctions alone and therefore an appropriate mix of incentives and occasional penalties will need to be designed and should be commensurate with the livelihoods and incomes of individuals or groups of users.

Particular care will be required to avoid locking in a rigid system of unchangeable quotas. Quotas will need to be flexible to adapt to interannual variability in water resources stocks, particularly in systems that predominantly use surface water. The development of water rights and formal allocation systems requires careful attention to hydrologic variability and temporal and geographical patterns of drought and surplus.

The impacts of climate change on water resource availability and variability will play an increasingly important role in water allocation, priority setting and in the flexibility that must be embedded in a water allocation framework. Regionally, there will be increasing pressure to restore environmental flows and this will increase pressure on agriculture as the bulk user and incentivize the specification and management of quotas.

The process of defining bulk and individual quotas has a technical basis but will need to be developed and negotiated with all users – the technical components include:

- establishing past water use under varying annual supply conditions and determining the component crop water use – it may be useful to also assess the physical and economic productivity of historical water use (this will require accurate land use mapping);
- examination of different quota options to meet basin, catchment and system level caps on water use – particular attention is required to examine the impacts of options on users' livelihoods, food security and health and associated incentives and compensation (this requires crop system and economic modelling, including detailed soil water-crop modelling to investigate cropping options that minimize water use and maximize returns to users, and in fully market-based economies this activity will likely be done as a series of scenarios, that internalize expected water user behaviour under different incentive and restriction conditions);
- a clear and transparent process of converting ET quotas to water delivery quotas and a process to track and match them to monitored consumptive use; and
- an information system that keeps users informed of how much water they have used and their likelihood of exceeding quota.

In the longer term, it is likely that users will seek to trade quotas in order to have more options for production and income that suit them.

4.9 Conclusions

This chapter introduced the basic concepts of consumption-based water management (CBWM) and has discussed the enabling possibilities of remote sensing estimates of actual evapotranspiration (ETa) and its strength in providing acceptably accurate data at a range of spatial and temporal scales.

CBWM requires both the prediction of crop water demand and the monitoring of ETa, with additional monitoring of effective rainfall, crop types and crop areas. In the near future, users will be provided with freely downloadable ET products, which lessens the burden of application in water management (whilst noting that onerous demands in training, storage hardware and other aspects of consumptive management will nonetheless remain). Calibration and validation, particularly of global RS-ET products will be required in situations where none has been done before.

Chapter 5. Consumption-based water management in Asia

5.1 Implementing consumption-based water management in Asia

Chapter 3 sets out the legal and governance mechanisms that must be in place before CBWM can be successfully implemented and achieve genuine water savings. Many of these elements have not yet been incorporated into water management practices in most Asian countries outside of China. The following sections explore some of these limitations in more detail.

Institutional

The number of government agencies with a stakeholder interest in water is significant (nearly 40 in some individual countries) and includes, in some instances, security agencies. However, siloed sectoral perspectives persist. That is, higher level policy coherence between agriculture, water, environment, cities, emergencies and industrial development is generally low. There are few clear lines of responsibility although some countries, such as Bangladesh, have established National Water Coordination Councils.

Decentralization of government is evident in many countries and has created new challenges in administrative capacity and policy coherence (understanding, formalization and implementation) across different levels of government. It has also clearly stretched technical capacity in poorer countries (Cambodia, the Lao People's Democratic Republic, Myanmar and Nepal), but has had less of an impact in others with greater resourcing and depth of expertise (China, Indonesia, Thailand and Viet Nam). In Indonesia, Irrigation Coordination Councils have been established across devolved provincial and city jurisdictions and sit in a coherent legislative framework, but so far have been less effective than hoped because of limited resources and lack of prioritization (SEI, 2021).

Legal and administrative

Water laws have been enacted or updated within the past ten years across most of the region. However, specific follow-up legislation clarifying water rights, agency responsibilities, co-management arrangements between state, private and community actors and mechanisms to improve water quality, have all lagged behind. Funding limitations probably explain the challenges associated with developing and implementing various aspects of these relatively new water laws, particularly where implementation goes hand in hand with decentralized water governance.

A good understanding of water tenure is rarely evident, especially knowledge and recognition of formal and informal water rights, customary rights (even those in abeyance), and de facto use which may or may not be legal but which in certain circumstances should be respected. Legal and administrative knowledge of local customary water rights and tenure arrangements is particularly poor and much that was known or historically integrated into the fabric of water administration has been progressively lost (for example, traditional and formalized water rights in irrigation systems in Sindh, and other parts of Pakistan (FAO, 2019) and between farmer managed irrigation systems and later state developments (for example, in Sumatra (Febriamansyah, 2001)). The landless generally have no water access rights for agriculture except in certain customary water management systems (for example, the karezat in Afghanistan, Pakistan and Iran (Turral, 1986).

Water accounting, extraction limits and allocations

Although considerable work has gone into establishing a variety of river basin management organizations across Asia, few have paid detailed attention to water accounting, extraction limits and water allocation, despite this being one of their fundamental tasks (FAO, forthcoming). Instead, flood forecasting, monitoring and management have tended to dominate in such organizations and as such are typically the focus of modelling, assessment and monitoring.

Modelling

Modelling capacity and use is extremely variable across countries in the region and is mostly conducted for very specific study purposes, often at the behest of aid/assistance projects. It seems rarer that studies are commissioned by high level policymakers for strategic management and assessment of options (SEI, 2021). Interestingly, modelling studies are increasingly being commissioned by provincial level government in Indonesia. Technical capacity is getting stronger everywhere and is already strong in some countries (Bangladesh, Indonesia and Thailand) but data limitations in relation to river flows, groundwater use and status, and abstractions for irrigation are evident, with the attendant danger of modelling with bad or incomplete data resulting in the classic modelling challenge of "garbage in, garbage out". Some countries (Indonesia and Thailand) are in the process of adopting central and automated data collection and warehousing, but many countries rely on transcription of paper records with continued challenges in timeliness, completeness, and loss or corruption of data. (FAO, forthcoming).

Data and data management

The work of relevant agencies across the region is undermined by poor or non-existing data. For example, hydrometric data across Asia is patchy at best and typically has poor spatial coverage and short time series (SEI, 2021), whereas local data with good spatial and temporal resolution (which is required for effective water accounting) tends to be lacking.

The extent to which global data sets can be usefully substituted for missing local data is not yet clear but will likely have limitations. To that end, much work is needed to improve local data sets in relation to groundwater, river flows, surface irrigation abstractions, connections between surface and groundwater, the fate and use of return flows in a river basin, water quality and some components of non-consumptive and partially consumptive use (urban water used for gardens and amenity purposes, for example).

Data management processing and handling also require considerable work. Fortunately, the costs of data management systems are decreasing and their effectiveness and reliability are improving. Web-based data storage and analysis is also an increasingly good option in terms of reliability, redundancy and cost-effectiveness, but it does require good internet connection and bandwidth. The increasing tendency to do intensive computation "in the cloud", for example with EEFlux and OpenET, also reduces the overhead on heavy data transfer, which accelerates the utility and availability of remote sensing analysis in Asia.

Training and capacity building

The geographic scope, number of countries and variety in socioeconomic and climatic conditions means that the training and capacity building needs of different agencies and countries with respect to routine water management, the development of good water accounting and allocation procedures, and eventually to implement CBWM where appropriate, varies considerably. However, and generally speaking, training and capacity building is required in relation to the following areas: hydrology; water accounting; remote sensing; environmental flows analysis; scenario building and modelling; data management; and law (including in relation to water tenure). In many countries, skills in climate modelling and climate change analysis have already received good attention and good capacity has been built and this now needs to be incorporated into water resources planning and management.

Many of these areas work synergistically. Thus, investment in the development of coordinated systems and institutions is required (noting that this is neither simple, nor cheap).

5.2 Costs and benefits – economic considerations

The costs of implementing CBWM, and before that developing effective water accounting, water rights and water allocation systems, are not insignificant and would invariably compete with other high-priority areas for funding.

To date, it has not been possible to compile a full set of costs for the Chinese pilot work in developing CBWM, in part because the full costs include significant research and development work, which would not be required in other countries in the future, and parallel reforms and development in the water and agriculture sector.

The main cost components to implement CBWM would consider:

1. governance including institutional change, legal development and the establishment and implementation of compliance mechanisms – potentially the transaction costs could be daunting, for example in groundwater management, and more specifically:

- the costs of widespread smart card metering for groundwater management would be significant, even though pilot experience in China and more recently in Bangladesh is very encouraging. In this case, a more decentralized and prioritized rollout in the most needed areas would be more cost-effective than attempting a national programme
- the transaction costs of issuing annual, individual water rights, as is currently practiced in pilot projects, is likely to be unworkable at larger scales in China itself and even more so elsewhere in Asia. It will be desirable to specify water rights or entitlements in more flexible and self-adjusting ways. There are good examples of how this might be done in Australia (entitlements, announced allocation and bulk entitlements) and elsewhere
- the registration of individual water rights in most Asian countries would be a massive and expensive task, which naturally leads to consideration of implementing a bulk entitlement process as a first step
- annual water quotas that are set using simple assessments of currently available water resources and likely augmentation through the (water) year are preferable to technically demanding and time-consuming modelling that has been used in the pilot CBWM work in China – such processes should fully take account of variability from year to year, and trends in water availability because of climate change

2. the establishment, staffing and equipment of dedicated water accounting units;
3. the establishment, staffing and equipment of remote sensing centres to measure consumptive use and associated work required to calibrate and validate data and methods;
4. improvement of hydrometric networks – despite improving and more cost-effective technology and the advent of the "internet of things", this remains very expensive and therefore is frequently not done, or not to the necessary density of measurement. Metering of individual pumps would be very desirable, but at even a very modest price of USD 50 per unit, the cost in India would exceed USD 1 billion for national coverage;
5. staffing costs for routine remote sensing analysis are likely to be modest. An assessment in Texas (Caldwell *et al.*, 2016) to use RS-ET to monitor consumptive use to manage compliance in water rights (mostly groundwater use) required:

- two full-time equivalent people (one full-time and two half-timers with different skills) for the whole state
- additional and unspecified staff time to identify the physical areas using water (crop mapping/irrigation area mapping) in order to apportion ET use from a licensing and regulatory perspective.

Given that rates, skills and available funding will vary considerably from country to country and possibly even within different river basins inside a country, detailed costing exercises are required. Since water accounting and allocation are long term, continuous and strategic activities, there is little point in developing systems that cannot be sustained with national funds (noting that pilot establishment using international assistance funds is unlikely to yield significant long-term benefits).

5.3 Implementing consumption-based water management in Asia

It is apparent that it will be some time before serious consideration is given to the development and implementation of CBWM in Asian countries outside China. Furthermore, it is unlikely to be appropriate in the Pacific region where water use in agriculture is modest and very diffuse. However, the most likely situations that will drive further interest and adoption include:

1. where already well-developed allocation systems cannot deliver the desired sustainability in water use. This will likely happen where water accounting for consumptive use is inadequate and there is substantial re-use of flows from one part of a river or groundwater basin to another. This hypothesis is supported by two water rights adjudications in New Mexico and Kansas in 2020, based on evidence about consumptive use derived from remote sensing (A. Keller, personal communication, 2021);
2. where detailed measurement and verification of flows is hard, for example in smallholder groundwater management in confined and geographically bounded aquifers. In this case, effective CBWM would likely require the definition of a groundwater management area that is not overly complex and would require associated cadastral mapping to define ownership of the lands using water and identification of pumpers;
3. where quotas and their management are well implemented across all sectors, including environmental water use, but where the effective, economic and equitable allocation of quota water within the agriculture sector at basin and regional levels within a country remains challenging. CBWM approaches will also be useful in adjusting water allocation procedures and quotas in response to the impacts of climate change; and
4. transboundary adjudication and assessment of water use. This case would not rely so much on CBWM but on application of the remote sensing techniques it uses. These techniques have already been applied in seeking to amend upper and lower basin water use and treaty obligations in the Colorado River Basin, where the river is shared by different states within the same Union (Stern and Sheikh, 2019).

5.4 Conclusions

A number of steps must be taken before CBWM can be implemented in most Asian countries. These steps imply considerable changes in governance, law, institutional mandates and capacity, and the acquisition of a range of specialist skills. Ideally, these changes would occur in concert with improved coordination and collaboration between government agencies and users and other relevant stakeholders. As in China, development and implementation ought to occur on a pilot basis, with this providing an opportunity to test and refine its application in a particular context – and to offer practical advice to other countries in the region considering its implementation.

Bibliography

Abubakr, M., Haider, B. & Zahoor, A. 2016. IoT enabled analysis of irrigation rosters in the Indus Basin irrigation system. *Procedia Engineering*. 154: 229–235. 12th International Conference on Hydroinformatics, HIC 2016.

Aither, 2018a. *A guide to managing water for the environment (a framing paper for the High Level Panel on Water*). Australian Water Partnership, Canberra.

Aither, 2018b. *WaterGuide: Setting a path to improved water management and use under scarcity (2nd edition)*. Canberra, Australian Water Partnership.

Allen, R.G., Pereira, L.S., Howell, T.A., & Jensen, M.E. 2011. Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management*, 98: 899–920.

Allen, R.G., Raes, D., & Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop requirements. *FAO Irrigation and Drainage Paper No*. 56, Rome, Italy.

Allen, R.G., Tasumi, M., & Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. *ASCE Journal of Irrigation and Drainage Engineering*, 133 (4): 380– 394.

Anderson, A., Allen, R.G., Morse, A. & Kustas, W.P. 2012. Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. *Remote Sensing of Environment*, 122: 50–65. doi:10.1016/j.rse.2011.08.025.

Anderson, E. P., Jackson, S., Tharme, R. E., Douglas, M., Flotemersch, J. E., Zwarteveen, M., Lokgariwar, C., Montoya, M., Wali, A., Tipa, G. T., Jardine, T. D., Olden, J. D., Cheng, L., Conallin, J,. Cosens, B., Dickens, C., Garrick, D., Groenfeldt, D., Kabogo, J., Roux, D. J., Ruhi, A. & Arthington, A. H. 2019. Understanding rivers and their social relations: a critical step to advance environmental water management. *WIREs Water*, 6: e1381.

Anderson, M.C., Kustas, W.P., Norman, J.M., Hain, C.R., Mecikalski, J.R., Schultz, L., González-Dugo, M.P., Cammalleri, C., d'Urso, G., Pimstein, A., & Gao, F. 2011. Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. *Hydrology and Earth System Sciences*, 15, 223.

Anderson, M.C., Norman, J.M., Diak, G.R., Kustas, W.P. & Mecikalski, J.R., 1997. A two- source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. *Remote Sensing of Environment* 60: 195–216.

Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.A. & Kustas, W.P. 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *Journal of Geophysical Research: Atmospheres*, 112(D1017).

Araral, E., & Yu, D. J. 2013. Comparative water law, policies, and administration in Asia: evidence from 17 countries. *Water Resources Research*. 49: 5307–5316.

Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B,. Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L., Richter, B.D. & Ward S. 2018. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). *Frontiers of Environmental* Science, 6: 45.

Asian Development Bank. 2013. *Asian water development outlook 2013: measuring water security in Asia and the Pacific*. Philippines.

Asian Development Bank. 2016. *Asian water development outlook 2016: strengthening water security in Asia and the Pacific.* Philippines.

Badiani-Magnusson, R., & Jessoe, K. 2013. *The impact of electricity subsidies on groundwater extraction and agricultural production.* Working Paper, University of California at Davis.

Badiani-Magnusson, R., & Jessoe, K. 2019. Electricity prices, groundwater, and agriculture: the environmental and agricultural impacts of electricity subsidies in India. In W. Schlenker., ed. *Agricultural productivity and producer behaviour*, pp. 157–183. Cambridge, MA, National Bureau of Economic Research.

Barker, R., & Molle, F. 2004. *Evolution of irrigation in South and Southeast Asia.* Comprehensive Assessment Research Report 5, IWMI. Colombo, Sri Lanka, Comprehensive Assessment Secretariat.

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., & Allen, R.G., 2005. SEBAL for spatially distributed ET under actual management and growing conditions. *ASCE Journal of Irrigation and Drainage Engineering*, 131 (1): 85–93.

Bastiaanssen, W.G.M., & Steduto, P. 2017. The water productivity score (WPS) at global and regional level: methodology and first results from remote sensing measurements of wheat, rice and maize. *Science of the Total Environment*, 575: 595–611.

Batchelor, C., Hoogeveen, J., Faures, J.M. & Peiser, L. 2016. Water accounting and auditing: a source book. *FAO Water Reports* 43. Rome. (Also available at https://www.fao.org/3/i5923e/I5923E.pdf).

Batchelor C, Reddy, V.R., Linstead, C., Dhar, M., Roy, S. & May, R. 2014. Do water saving technologies improve environmental flows? *Journal of Hydrology*, 518: 140–149.

Batchelor, C. & Schnetzer J. 2018. *Compendium of climate-smart irrigation.* Rome, GACSA/FAO. (Also available at www.fao.org/gacsa/en/).

Bird, J., Lincklaen Arriens, W., & Von Custodio, D. 2009. *Water rights and water allocation: issues and challenges for Asia.* Manila, Asian Development Bank.

Birkenholtz, T. 2017. Assessing India's drip-irrigation boom: efficiency, climate change and groundwater policy. *Water International*, 42(6): 663–677.

Blackwatch Consulting. 2020. *Cambodia irrigation performance assessment project final report.* Bangkok, FAO RAP.

Booker, J.F. & Young, R.A. 1991. *Economic impacts of alternative water allocation institutions in the Colorado River Basin.* Research Project Technical Completion Report No. 161. Colorado Water Resources Research Institute, Colorado State University.

Budyko, M. I. 1948. *Evaporation under natural conditions*. Gidrometeorizdat, Leningrad. English translation by IPST, Jerusalem.

Bunn, S.E. 2003. Healthy river ecosystems: vision or reality? *Water* 30.

Calder, I,. Gosain, A., Rama Mohan Rao, M.S., Batchelor, C., Garratt, J. & Bishop, E. 2007. Watershed development in India. 2. New approaches for managing externalities and meeting sustainability requirements. *Environ Development and Sustainabiity*, 10(4).

Caldwell, T., Huntington, J., Scanlon, B., Joros, A. & Howard, T. 2017. Improving irrigation water use estimates with remote sensing technologies: a feasibility study for Texas. Final Project Report. Bureau of Economic Geology, Desert Research Institute and Center for Space Research.

Calera, A. , Isidro, C., Osan, A., D'Urso, G. & Menenti, M. 2017. *Remote sensing for crop water management: From ET modelling to services for the end users. Sensors*, 17 (5), 1104.

Cameron, H. & Cameron, S. 2012. Compliance and enforcement of water licenses in NSW: limitations in law, policy and institutions. *The Australasian Journal of Natural Resources Law and Policy*, 15(2): 149–189.

Cammalleri, C., Anderson, M.C., Gao, F., Hain, C.R. & Kustas, W.P. 2013. A data fusion approach for mapping daily evapotranspiration at field scale. Water Resources Research, 49: 4672–4686, Cammalleri, C., Anderson, M.C., Gao, F., Hain, C.R, & Kustas, W.P. 2014. Mapping daily evapotranspiration at field scales over rainfed and irrigated agricultural areas using remote sensing data fusion. *Agricutural Forestry and Meteorology.*, 186: 1–11.

Carmody, E. 2017. Climate change is water change: integrating water management, mitigation and adaptation laws and policies. *Australian Environment Review*, 31(10): 358–363.

Carmody, E. 2019. *Analysis: are our water laws climate ready?* 10th Annual Legalwise Water Symposium. 18 October 2019. Sydney, Australia.

Carmody, E. & Slapp, K. 2020. *Case summary: corporate irrigator found guilty of breaching the Water Management Act.* [online]. [Cited 01 November 2020]. https://www.edo.org.au/2020/10/01/case-summary- corporate-irrigator-found-guilty-of-breaching-the-water-management-act/

Castle, S. L., Reager, J. T., Thomas, B. F., Purdy, A. J., Lo, M.-H., Famiglietti, J. S. & Tang, Q. 2016. Remote detection of water management impacts on evapotranspiration in the Colorado River Basin. *Geophysical Research Letters*, 43: 5089–5097.

Chambers, S. 2003. Deliberative democratic theory. *Annual Review of Political Science 6, 307–326. Chen, H. 2019. RS-ET validation across different environments and crops in China.* FAO–China Institute of Hydraulic and Water Resources Research Expert Consultation on consumption based water management, Beijing 29-30 October 2019.

Craig, D., & Gachenga, E. 2009. The recognition of indigenous customary law in water resource management. *The Journal of Water* Law, 20(5).

Crase, L., Cooper, B., & Burton, M. 2019. From sharing the burden of scarcity to markets: ill-fitting water property rights and the pressure of economic transition in South Asia. *Water*, 11: 1294.

Damania, R., Desbureaux, S., Rodella, A.S., Russ, J., & Zaveri, E. 2019. *Quality unknown: the invisible Water crisis*. Washington, DC: World Bank.

Donohue, R. J., Roderick, M. L. McVicar, T. R. & Farquhar, G. D. 2013. Impact of CO2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, 40: 3031– 3035,

Dore, J. 2014. An agenda for deliberative water governance arenas in the Mekong. *Water Policy*, 16(S2): 194– 214.

Dryzek, J. S, Bächtiger, A., Chambers, S., Cohen, J., *et al.* 2019. The crisis of democracy and the science of deliberation: citizens can avoid polarization and make sound decisions. *Science*, 363 (6432), 1144–1146.

Dudgeon, D. 2000. Conservation of freshwater biodiversity in Oriental Asia: constraints, conflicts, and challenges to science and sustainability. *Limnology*, 1, 237–243.

EIA. 2019. *International energy outlook 2019 with projections to 2050.* U.S. Energy Information Administration, U.S. Department of Energy, Washington DC. (Also available online https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf).

ESCAP. 2020. *Ready for the dry years: building resilience to drought in Southeast Asia.* Bangkok (2nd edition). (Also available https://www.unescap.org/sites/default/d8files/knowledge- products/Ready_for_the_Dry_Years_Second_edition.pdf.pdf).

European Environment Agency. 2021. *Water resources across Europe – confronting water stress: an updated assessment. EEA Report 12/2021.* [online]. [Accessed November 2021]. https://www.eea.europa.eu/publications/water-resources-across-europe-confronting

Evett, S.R., Kustas, W.P, Gowda, P.H. Anderson, M.C., Prueger, J.H. &. Howell, T.A. 2012. Overview of the bushland evapotranspiration and aAgricultural remote sensing experiment 2008 (BEAREX08): A field experiment evaluating methods for quantifying ET at multiple scales. *Advances in Water Resources*, 50: 4—19.

Falkenmark, M., & J. Rockström. 2004, Balancing water for humans and nature. *The new approach in ecohydrology.* London, Earthscan, 247 pp. FAO. forthcoming. Policies to manage water research in Asia. Rome.

FAO. undated. Incentives for ecosystem services: supporting the transition to sustainable food systems. (also available at www.fao.org/3/a-i4702e.pdf).

FAO. 2008. Coping with water scarcity – an action framework for agriculture and food security. *FAO Water Reports* 38. Rome. (Also available at https://www.fao.org/3/i3015e/i3015e.pdf).

FAO. 2018a. *Asia and the Pacific regional overview of food security and nutrition 2018 – accelerating progress towards the SDGs.* Bangkok. (Also available at www.fao.org/3/ca0950en/ca0950en.pdf).

FAO. 2018b. *Dynamic development, shifting demographics, changing diets.* Bangkok. 172 pp. (Also available at www.fao.org/3/i8499en/i8499EN.pdf).

FAO. 2019. *Water policy for Sindh, draft for discussion.* FAO internal document. Islamabad, Pakistan.

FAO. 2021a. AQUASTAT-FAO's global information system on water and agriculture. [online]. [Accessed 22 June 2021]. https://www.fao.org/aquastat/en/overview/methodology/water-use

FAO. 2021b. *WaPOR, remote sensing for water productivity.* [online]. [Accessed 2 July 2021]. https://www.fao.org/in-action/remote-sensing-for-water-productivity/en/

FAO, IFAD, UNICEF, WFP & WHO. 2019. *The State of food security and nutrition in the world 2019: safeguarding against economic slowdowns and downturns.* Rome. (Also available at www.fao.org/3/ca5162en/ca5162en.pdf).

García, L., Rodríguez, D., Wijnen, M. & Inge Pakulski, I., eds. 2016. *Earth observation for water resources management: current use and future Diego J opportunities for the water sector.* Washington, DC, World Bank Group.

GEF TWAP. undated. Global Environment Fund Transboundary Waters Assessment Programme. [online portal]. [Accessed 23 August 2020]. http://geftwap.org/data-portal

Giordano, M., and K. G. Villholth, eds. 2007. *The agricultural groundwater revolution: opportunities and threats to development.* Comprehensive Assessment of Water Management in Agriculture Series 3. Wallingford, U.K., CABI.

Giorgi, F. 2019. Thirty years of regional climate modelling: where are we and where are we going next? *Journal of Geophysical Research: Atmospheres*, 124: 5696–5723.

Grafton, Q.R. 2019. Policy review of water reform in the Murray-Darling Basin, Australia: the 'do's' and 'do nots'. *Australia Journal of Agricultural and Resource Economics*, 63(1): 116–141.

Grafton, Q.R., Williams, J., Perry, C.J. & Molle, F. 2018. The paradox of irrigation efficiency. *Science* 361(6404): 749–750.

Guerschman J.-P., van Dijk, A.I.J.M., McVicar, T.R., van Niel, T.G., Li. L., Liu, Y. & Peña-Arancibia, J. 2008. *Water balance estimates from satellite observations over the Murray-Darling Basin.* A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields project, CSIRO Australia. 93 pp.

GWP (Global Water Partnership). 2000. *Integrated water resources management. TAC Background Paper No.4.* [online]. Stockholm, Sweden. [Accessed 15 May 2021]. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water- resources-management-2000-english.pdf.

Hanemann, M. & Young, M. 2020. Water rights reform and water marketing: Australia vs the US West. *Oxford Review of Economic Policy*, 36(1): 108–131.

Hodgson, S. 2006. Modern water rights: theory and practice. *FAO Legislative Study 92.* [online]. [Accessed 30 August 2021]. https://www.fao.org/3/a0864e/a0864e.pdf

Hodgson S, 2016. Exploring the concept of water tenure. *FAO Land and Water Discussion Paper 10.* (also available at https://www.fao.org/publications/card/en/c/f5d1fc87-ac13-438d-8957-4f7214b0ea55/).

Holland, R.A., Scott, K.A., Florke, M., Brown, G., Ewers, R.M., Farmer, E., Kapos, V., Muggeridge, A., Scharlemann, J.P.W., Taylor, G., Barrett, J., & Eigenbrod, F. 2015. Global impacts of energy demand on the freshwater resources of nations. *Proceedings of the National Academy of Sciences.* 112(48): E6707–E6716.

Holley, C. 2012. Compliance and enforcement of water licences in NSW: limitations in law, policy and institutions. *The Australasian Journal of Natural Resources Law and Policy*, 15(2): 149–189.

Horne, A.C., O'Donnell, E.L., Loch, A.J., Adamson, D.C., Hart, B., & Freebairn, J. 2018. Environmental water efficiency: maximising benefits and minimising costs of environmental water use and management. *Wiley Interdisciplinary Reviews: Water*, 5(6):e1285.

ICIMOD. 2017: *A multi-dimensional assessment of ecosystems and ecosystem services at Inle Lake, Myanmar.* ICIMOD Working Paper 2017/17. Nepal, International Centre for Integrated Mountain Development (ICIMOD).

International Environmental Law Research Centre. 2016. *Model Groundwater (Sustainable Management) Act 2016.* [online]. [Accessed 30 May 2021]. http://www.ielrc.org/content/e1605.pdf

International River Foundation. 2007. *The Brisbane Declaration.* [online]. [Accessed 23 May 2021]. https://riverfoundation.org.au/wp-content/uploads/2017/02/THE-BRISBANE-DECLARATION.pdf

International Water Centre. *River health and environmental flow in China.* Undated. [online]. [Accessed 18 October 2020] http://www.watercentre.org/projects/case-studies/river-health-and-environmental-flow-in- china/

Irrigation Australia. undated. *Irrigation Australia guidelines for the use of tamper evident seals on non-urban water meters.* Undated. [online]. [Accessed 15 November 2020]. https://www.irrigationaustralia.com.au/documents/item/1067

IWHR. 2019. *Consumption-based water management. Zero Draft Discussion Paper.* China Institute of Water Resources and Hydropower Research, Beijing.

Jackson, R. 1984. Remote sensing of vegetation characteristics for farm management. In *Proc. SPIE 0475, Remote sensing: critical review of technology*, pp. 81–96. (16 October 1884). [online]. [Accessed 12 March 2021]. https://www.spiedigitallibrary.org/conference-proceedings-of-SPIE/0475.toc

Jia, Y. 2011. Groundwater issues and management in the North China Plain. In A.N. Findikakis and K. Sato, eds. *Groundwater Management Practices*, pp. 1–12. London, CRC Press.

Jiang, M. 2018. *Recent developments of water trading in China*. University of Nottingham: Asia Research Institute. Available at http://theasiadialogue.com/2018/05/29/recent-developments-of-water-trading-in- china/.

Jimenez, A., Saikia, P., Gine, R., Avello, P., Leten, J., Lymer, B.L., Schneider, K., & Ward, R. 2020. Unpacking water governance: a framework for practitioners. *Water*, 12(13): 827.

Kallio, M, 2020. Regional mapping of water scarcity in Asia and the Pacific. FAO-RAP Water Scarcity Programme, Bangkok.

Kalma, J.D., McVicar, T.R., & McCabe, M.F., 2008. Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data. *Surveys in Geophysics*, 29: 421–469.

Karimi, P. & W. G. M. Bastiaanssen. 2015. Spatial evapotranspiration, rainfall and land use data in water accounting- Part 1: Review of the accuracy of the remote sensing data. *Hydrolgy of. Earth System Sciences*, 19: 507-532; doi 10.5194/hess-19-507-2015.

Kaune, A., Droogers, P., van Opstal, J. Perry, C. & Steduto, P. 2020. *REWAS: REal WAter Savings tool: technical document.* FutureWater Report 200. Wageningen, The Netherlands.

Kendy, E., Apse, C. & Blann, K. 2012. *Practical guide to environmental flows for policy and planning with nine case studies in The United States*, with selected case studies by Mark P. Smith and Alisa Richardson. The Nature Conservancy.

Kimura de Freitas, G. 2008. *Methods and tools for determining environmental flows*. GEF IW: LEARN Regional Workshop on Application of Environmental Flows in River Basin Management. 11 – 15 February 2008.

Kite, G.W., & Droogers, P., 1999. Comparing evapotranspiration estimates from satellites, hydrological models and field data. *Journal of Hydrology*, 229: 2–18.

Li, Y., Wang, H., Chen, Y., Deng, M., Li, Q., Wufu, D., Wang, D. & Ma, L. 2020. Estimation of regional irrigation water requirements and water balance in Xinjiang, China during 1995–2017. *PeerJ* 8: e8243.

Linstead, C. 2018. The contribution of improvements in irrigation efficiency to environmental flows. *Frontiers in Environmental Science.* 6: 1–6.

Liu, B., & Speed, R. 2009. Water resources management in the People's Republic of China. *Water Resources Development*. 25(2): 193–208.

Liu, S.F., Xiong, J., & Wu, B.F., 2011. *ETWatch: a method of multi-resolution ET data fusion. Journal of Remote Sensing*, 15 (2): 55–69.

Liu, S.M., 2010. *Independent ground validation report of remote sensing evapotranspiration (ET) in Hai River Basin*. Beijing Normal University, School of Geography.

Liu, S.M., Xu, Z.W., Wang, W.Z., , Z.Z., Zhu, M.J., Bai, J., & Wang, J.M. 2011. A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem. *Hydrology of Earth System Sciences*, 15: 1291–1306.

Loch, A., Pérez-Blanco, C.D., Carmody, E., Felbab-Brown, V., D. Adamson, D. & Seidl, C. 2020. Grand theft water and the calculus of compliance. *Nature Sustainability*, 3: 1012–1018.

Matthews, K. 2017. *Independent investigation into NSW water management and compliance*: interim report. 8 September 2017. NSW Department of Industry, Australia.

Maupin, M.A., Ivahnenko, T., & Bruce, B., 2018, *Estimates of water use and trends in the Colorado River Basin, Southwestern United States*, 1985–2010. U.S. Geological Survey Scientific Investigations Report 2018–5049.

McMahon T.A, Finlayson, B.L., Haines, A. & Srikanthan, R. 1987. Runoff variability: a global perspective. In Solomon, S.I., Beran, M. & Hogg, W., eds. *The influence of climate change and climatic variability on the hydrologic regime and water resources.*, pp. 3–11. Proceedings of a symposium held during the XIX Assembly of the International Union of Geodesy and Geophysics at Vancouver, August 1987. Publication No. 186. [online]. [Accessed 14 August 2021]. http://hydrologie.org/redbooks/168.htm

McVicar, T.R., Zhang, G., Bradford, A.S., Wang, H., Dawes, W.R., Zhang, L., & Li, L., 2002. Monitoring regional agricultural water use efficiency for Hebei Province on the North China Plain. *Australian Journal of Agricultural Research*, 53: 55–76.

MDBA. 2010. *Guide to the proposed basin plan: overview.* Murray–Darling Basin Authority, Canberra.

MDBA. 2016. *The triple bottom line framework. A method for assessing the economic, social and environmental outcomes of the sustainable diversion limits in the northern basin.* Murray–Darling Basin Authority, Canberra.

MDBA. 2019. *Annual progress report : the sustainable diversion limit adjustment mechanism.* Murray–Darling Basin Authority, Canberra. [online]. [Accessed 13 September 2021]. https://www.mdba.gov.au/sites/default/files/pubs/SDLAM-annual-progress-report-2018_0.pdf

Millennium Ecosystem Assessment. 2005. Chapter 7 Freshwater ecosystem services. In *Ecosystems and human well-being: policy responses*, pp. 213–255.

Ministry of Water Resources, Peoples' Republic of China. undated. *Water resources management and protection in China.* Brief in English. [online]. Beijing. [Accessed 22 January 2021]. http://www.mwr.gov.cn/english/

Molden, D. 1997. *Accounting for water use and productivity.* SWIM Paper 1. Colombo, Sri Lanka, International Irrigation Management Institute.

Molden, D., ed. 2007. *Water for food water for life: a comprehensive assessment of water management in agriculture.* London, Routledge.

Molden D. J., Keller, J., & Sakthivadivel, R. 2001. *Hydronomic zones for developing basin water conservation strategies. Research Report 56*. Colombo, Sri Lanka, International Water Management Institute.

Molden, D., Murray-Rust, H., Sakthivadivel, R. & Makin, I. 2003. A water- productivity framework for understanding and action. In J.W. Kijne, R. Barker, & D. Molden, eds. *Water productivity in agriculture: Limits and opportunities for improvement*, pp. 1–18. Wallingford, IWMI & CABI Publishing,

Molle, F. & Wester, P., eds. 2009. *River basin trajectories: societies, environments and development.* CABI and International Water Management Institute. [online]. [Accessed 12 November 2020]. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/River_Basin_Trajectories/978184 5935382.pdf

Molle, F. & Berkoff, J. 2006. *Cities versus agriculture: revisiting intersectoral water transfers, potential gains and conflicts.* Comprehensive Assessment Research Report 10. Colombo, Sri Lanka, International Water Management Institute.

Moomaw, W.R., Chmura, G.L. Davies, G.T., Finlayson, C.M., Middleton, B.A., Natali, S.M., Perry, J.E., Roulet, N., & Sutton-Grier, A.E. 2018. Wetlands in a changing climate: science, policy and management. *Wetlands* 38: 183–205.

Moore, S. 2019. Legitimacy, development and sustainability: understanding water policy and politics in contemporary China. *The China Quarterly*, 237: 153–173.

Muhammad, A., Haider, B. & Ahmad, Z. 2016. IoT enabled analysis of irrigation rosters in the Indus Basin irrigation system. *Procedia Engineering* 154: 229–235.

Mukherji, A., & Facon, T. 2009. *Revitalizing Asia's Irrigation: to sustainably meet tomorrow's food needs.* Colombo, Sri Lanka, IWMI and Rome, FAO.

National Bureau of Statistics of China. 2019. *China Statistical Year Book*, 2019. China Statistics Press, Beijing. [online]. Accessed March 2020]. http://www.stats.gov.cn/tjsj/ndsj/2019/index.html

Natural Resources Access Regulator (NRAR). 2020. *Natural Resources Access Regulator.* [online]. [Accessed 01 November 2020]. https://www.dpie.nsw.gov.au/nrar

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agricultural and Forest Meteorology*, 77(3-4): 263–293.

Norton, B.G. 2012. Valuing ecosystems. *Nature Education Knowledge*, 3(10): 2.

OpenET. 2021. *Filing the biggest data gap in water management.* [online]. [Accessed 2 July 2021]. https://openetdata.org/

Papas, M. 2018. Supporting sustainable water management: insights from Australia's reform journey and future directions for the Murray–Darling Basin. *Water*, 10(11): 1649.

Pérez-Blanco, C.D., Hrast-Essenfelder, A. & Perry, C. 2019. Irrigation technology and water conservation: from panaceas to actual solutions. In L.Garrote, G. Tsakiris, V.A. Tsihrintzis, H. Vangelis & D. Tigkas, eds. *Proceedings of the world congress on water resources and environment: managing water resources for a sustainable future*, pp. 499–500. Madrid, Spain, 25–29 June 2019 [online]. [Accessed 22 July 2020]. http://ewra.net/pages/EWRA2019_Proceedings.pdf

Perry, C. 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage*, 56: 367–78.

Perry, C. 2012. Accounting for water: stocks, flows, and values. In UNU-IHDP & UNEP. *Inclusive wealth report 2012. Measuring progress toward sustainability*, pp. 215–230. Cambridge, Cambridge University Press.

Perry C. 2019. Learning from water footprints – who loses, who wins and who cares? *Policy Quarterly*, 15 (3):70–74.

Perry, C. & Steduto, P. 2017. *Does improved irrigation technology save water? A review of the evidence. Discussion paper on irrigation and sustainable water resources management in the Near East and North Africa.* Regional Initiative on Water Scarcity for the Near East and North Africa. Cairo, FAO. (Also available at https://www.fao.org/3/I7090EN/i7090en.pdf).

Perry, C., Steduto, P., Allen, R.G. & Burt, C.M. 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. *Agricultural Water Management*, 96 (11): 1517–1524.

Piesse, M. 2020. *Global water supply and demand trends point towards rising water insecurity.* Future Directions International [online]. Australia [Accessed 22 August 2021]. https://www.futuredirections.org.au/publication/global-water-supply-and-demand-trends-point-towards-rising-water-insecurity/

Pittock, J., Grafton, R.Q. & Williams, J. 2015. The Murray-Darling Basin Plan fails to deal adequately with climate change. *Water*, 42(6): 28–34.

Primmer, E., Jokinen, P., Blicharska, M., Barton, D.N., Bugter, R., & Potschin, M. 2015. Governance of ecosystem services: a framework for empirical analysis. *Ecosystem Services*, 16: 158–166.

Ramazzotti, M. 2008. *Customary water rights and contemporary water legislation: mapping out the interface.* FAO Legal Papers Online No 76. [online]. Rome. [Accessed 12 June 2021]. https://www.fao.org/fileadmin/user_upload/legal/docs/lpo76.pdf

Ramsar. 2002. New guidelines for management planning for Ramsar sites and other wetlands. [online]. [Accessed 12 November 2020]. https://www.ramsar.org/sites/default/files/documents/library/new-mgt-guide.pdf

Richardson, J. 2017. *Post-colonial evolution of water rights in India and the United States. In S. Pellissery, B. Davy & H. Jacobs, eds. Land policies in India: promises, practices and challenges*, pp. 51–70. Singapore, Springer.

Rosa, L., Chiarelli, D.D., Sangiorgio, M., Beltran-Peña, A.A., Rulli, M.C., D'Odorico, P. & Fung, I. 2020. Potential for sustainable irrigation expansion in a 3°C warmer climate. *Proceedings of the National Academy of Sciences*, 117(47): 29526–29534.

Rosegrant, M.W., Cai, X. & Cline, S.A. 2002. Balancing water for food and the environment. In *World water and food 2015: dealing with scarcity*, pp. 155–175. Washington, DC, International Food Policy Research Institute.

Sadras, V, Grassini, P. & Steduto, P. 2007. *Status of water use efficiency of main crops.* FAO Solaw Background Thematic Report – TR07. (Also available at https://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_07_web.pdf).

Sadras V. & Mcdonald G. 2012. *Water use efficiency of grain crops In Australia: principles, benchmarks and management.* Australian Government, Grains Research and Development Corporation.

Satoh, Y., Kahil, T., Byers, E., Burek, P., Fischer, G., Tramberend, S., Greve, P., Florke, M., Eisner, S., Hanasaki, N., Magnuszewski, P., Nava, L.F., Cosgrove, W., Langan, S., & Wada, Y. 2017. Multi-model and multi-scenario assessments of Asian water futures: the water futures and solutions (WFaS) initiative. *Earth's Future*, 5(7): 823–852.

Scodanibbio, L. 2011. Opening a policy window for organisational change and full-cost accounting: the creation of BC Hydro's water use planning program. *Ecological Economics*, 70(5): 1006–1015.

Seckler D. 1996. *The new era of water resources management.* Research Report 1. IIMI, Colombo. ISBM 92- 9090-325-2

SEI (Piman, T., Chuthong, J., & Ghilmire, U.) 2021. *Understanding water modeling capacity and use in the Asia Pacific Region.* Final Synthesis Report. Stockholm Environment Institute and Food and Agriculture Organization, Bangkok, Thailand.

Senay, G. Leake, B.S., Nagler, P.L., Artan, G., Dickinson, J., Cordova, J.T. & Glenn, E.P. 2011. Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods. *Hydrological Processes*, 25: 4037–4049.

Shah, T. 2007. The groundwater economy of South Asia: an assessment of size, significance and socio- ecological impacts. In M. Giordano & K. G. Villholth, eds. *The agricultural groundwater revolution: opportunities and threats to development*, pp. 7–36. Wallingford, UK, CABI.

Shah, T. 2009. *Taming the anarchy: groundwater governance in South Asia.* Washington, DC, Resources for the Future; Colombo, Sri Lanka, International Water Management Institute (IWMI). 310 pp.

Shen, D. & Speed, R. 2009. Water resources allocation in the People's Republic of China. *International Journal of Water Resources Development*, 25(2): 209–225.

Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *Water International*, 25(1): 11– 32.

Shiklomanov, I.A. & Rodda, J.C. 2004. *World water resources at the beginning of the 21st Century.* UK, Cambridge University Press, 435 pp.

Sidhu BS, Kandlikar M, Ramankutty N. 2020. *Power tariffs for groundwater irrigation in India: A comparative analysis of the environmental, equity, and economic tradeoffs.* World Development, Volume 128,104836, ISSN 0305-750X. (Also available online https://www.sciencedirect.com/science/article/pii/S0305750X19304851)

Sidle, R.C., Ziegler, A.D., & Vogler, J.B. 2007. Contemporary changes in open water surface area of Lake Inle, Myanmar. *Sustainability Science*. 2: 55–65.

Simons, G.W.H., Bastiaanssen, W.G.M. & Immerzeel, W.W. 2015. Water reuse in river basins with multiple users: a literature review. *Journal of Hydrology* 522: 558–571.

Small, N., Munday, M., & Durance, I. 2017. The challenge of valuing ecosystem services that have no material benefits. *Global Environmental Change*, 44: 57-67.

Smith, S.M. 2019. Instream flow rights within the prior appropriation doctrine: insights from Colorado. *Natural Resources Journal.* 59(1): 181–213.

Stanford Law School (Afghanistan Legal Education Project). 2015. *An introduction to the property law of Afghanistan.* 1st edition. CA, Stanford Law School.

Statista. 2021. *Principal rice exporting countries worldwide in 2020/2021.* [online]. [Accessed 13 February 2021]. https://www.statista.com/statistics/255947/top-rice-exporting-countries-worldwide-2011/

Steduto. P. 2019. *Addressing the accuracy for RS-ET data and their field validation.* FAO Expert Consultation on Consumption-Based Water Management, IWHR, Beijing, 29–30 October 2019.

Steduto, P., Hsiao, T.C., Fereres, E. & Raes, D. 2012. *Crop yield response to water.* FAO Irrigation and Drainage Paper 66. Rome, FAO.

Stephens, C.M., McVicar, T.R., Johnson, F.M. & Marshall, L.A. 2018. Revisiting pan evaporation trends in Australia a decade on. *Geophysical Research Letters* 45(20): 11,164–11,172.

Stern, C.V. & Sheikh, P.A. 2019. *Management of the Colorado River: water allocations, drought, and the federal role.* Updated November 25, 2019. Congressional Research Service Report. [online]. [Accessed 23 February 2021]. https://crsreports.congress.gov/product/pdf/R/R45546/11

Szeptycki, L. & Pilz, D. 2017. *Colorado River Basin environmental water transfers score card.* Stanford Woods Institute for the Environment. [online]. [Accessed 22 March 2021]. https://stacks.stanford.edu/file/druid:rr649dj2687/Co_River_Basin_Env_Transfers_Scorecard.pdf

Taniguchi, M., Endo, A., Gurdak, J., & Swarzenski, P. 2017. Water-energy-food nexus in the Asia-Pacific region. *Journal of Hydrology: Regional Studies*, 11: 1–8.

Tasumi, M., Allen, R.G. & Trezza, R. 2006. Calibrating satellite-based vegetation indices to estimate evapotranspiration and crop coefficients. In D. Wichelns & S. Anderson, eds. *Ground water and surface water under stress: competition, interaction, solutions*, pp. 103–112. A USCID Water Management Conference, Boise, Idaho, October 25–28, 2006.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., R. Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J-F., Holman, I. & Treidel , H. 2013. Groundwater and climate change. *Nature Climate Change*, 3: 322–329.

Te Boekhorst, D. G. J., Smits, T. J. M., Yu, X., Li, L., Lei, G. & Zhang, C. 2010. Implementing integrated river basin management in China. *Ecology and Society*, 15(2): 23.

Thapa, B.R., Ishidaira Hm Pandey, V.P., Bhandari, T.M. & Shakya, N.M. 2018. Evaluation of water security in Kathmandu Valley before and after water Transfer from another basin. *Water*, 10(2): 224.

Trancoso, R., Larsen, J.R., McVicar, T.R., Phinn, S.R. & McAlpine, C.A. 2017. CO2-vegetation feedbacks and other climate changes implicated in reducing base flow. *Geophysical Research Letters*, 44(5): 2310–2318.

Trisurat, Y., Aekakkararungroj, A., Ma, H. O., & Johnston, J. M. 2018. Basin-wide impacts of climate change on ecosystem services in the Lower Mekong Basin. *Ecological research*, 33(1): 73–86.

Turral H. 1986. *Land revenue records in Baluchistan, a note.* Small Scale Irrigation Schemes Development Project, Quetta, Baluchistan, Pakistan.

Turral, H.N., Faures, J.M. & Burke, J.A. 2011. *Climate change, water and food security.* FAO Water Reports 36. Rome. (Also available at https://www.fao.org/3/i2096e/i2096e.pdf).

Turral, H. & Wood, M. 2013. *Modernisation in irrigated agriculture in Australia: a review.* OECD country case study for the World Bank EAP IMM Regional Project (P130522). Washington, DC, World Bank.

UNDESA. 2014. *Water and food security.* [online]. [Accessed 17 August 2021].
https://www.un.org/waterforlifedecade/food_security.shtml

UNDP. 2015. *Inle Lake conservation and rehabilitation: stories from Myanmar.* Myanmar, United Nations Development Programme. (Also available at https://www.mm.undp.org/content/myanmar/en/home/library/environment_energy/inle-lake-conservation- and-rehabilitation--stories-from-myanmar.html).

UNEP. 1992. *Rio Declaration on Environment and Development*, Annex 1, UN Doc A/CONF.151/26. Nairobi, United Nations Environment Programme. [online]. [Accessed 3 January 2021]. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_C ONF.151_26_Vol.I_Declaration.pdf

UNEP. 2019. *Environmental rule of law: first global report.* Nairobi, United Nations Environment Programme. (Also available at https://www.unep.org/resources/assessment/environmental-rule-law-first-global-report).

UNEP-DHI &UNEP. 2015. *Transboundary river basins: status and future trends. Summary for policy makers.* Transboundary Waters Assessment Programme. Nairobi, United Nations Environment Programme. (Also available at http://www.geftwap.org/publications/river-basins-spm).

UNESCO. 2020. *The United Nations world water development report 2020: water and climate change.* Paris, United Nations Educational, Scientific and Cultural Organization. (Also available at https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en).

UNGA. 2015. *Transforming our world: the 2030 Agenda for Sustainable Development.* A/RES/70/1. New York, United Nations General Assembly.

USDI (United States Department of Interior). 2012. *Colorado Basin water supply and demand study*: executive summary, Dec 2012. Bureau of Reclamation. USBR, 2012. Water Supply and Demand Study (Colorado Basin). Executive Summary, Dec 2012.

van Opstal, J., Droogers, P., Kaune, A., Steduto, P. & Perry., C. 2021. *Guidance on realizing real water savings with crop water productivity interventions.* FAO Water Reports 46. Wageningen, FAO and FutureWater. (Also available at https://www.fao.org/documents/card/en/c/cb3844en).

Vidal, A., ed. 2000. *Remote sensing and geographic information systems in irrigation and drainage – methodological guide and applications.* New Delhi, India, International Commission on Irrigation and Drainage.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., & Bierkens, M.F.P. 2010. Global depletion of groundwater resources. *Geophysical Research Letters*, 37(20).

Walker F. 2010. *Incorporating climate change in water allocation planning.* Waterlines Report 28. Canberra. Australia, National Water Commission.

Ward, F.A. & Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences of the United States of America*, 105 (47): 18215–18220.

Wentworth Group of Concerned Scientists. 2020. *Assessment of river flows in the Murray–Darling Basin: observed versus expected flows under the Basin Plan 2012–2019.* Sydney. (Also available at https://wentworthgroup.org/wp-content/uploads/2020/08/MDB-flows.pdf).

Wester, P., Mishra, A., Mukherji, A. & Shrestha A. B., eds. 2019. *The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people.* Switzerland AG, Cham., Springer Nature.

Wheeler, S.A., Carmody, E., Grafton, R.Q., Kingsford, R.T. & Zuo, A. 2020. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. *Resources, Conservation and Recycling*, 159.

Willardson, L.S., Allen, R.G. & Frederiksen, H.D. 1994. *Universal fractions and the elimination of irrigation efficiencies.* 13th Technical Conference, US Commission on Irrigation and Drainage, Denver, CO, 19–22 October 1994.

Wilson Water Group. 2015. Historic crop consumptive use analysis: Colorado River Basin. Final Report. *World Bank. 2003. *Water user association development in China: participatory management practice under Bank-supported projects and beyond.* Social Development Notes No. 83. Washington DC.

World Bank. 2010. Deep wells and prudence: towards pragmatic action for addressing groundwater overexploitation in India. [online].[Accessed 12 March 2021]. https://openknowledge.worldbank.org/handle/10986/2835

World Bank. 2011a. *China: water pricing & water user associations sustainability.* Washington DC.

World Bank. 2011b. *Implementation completion and results report*, GEF Hai Basin Integrated Water and Environment Management Project. Beijing.

World Bank. 2013. *Design of ET-based water rights administration system for Turpan Prefecture of Xinjiang China.* Washington DC.

World Bank. 2016. *World feminization of agriculture in the context of rural transformations: what is the evidence?* Working Paper No. ACS20815. Washington, DC.

World Bank. 2019. *New avenues for remote sensing applications for water management: a range of applications and the lessons learned from implementation.* Washington, DC.

World Bank. 2020. *Managing Groundwater for Drought Resilience in South Asia.* Washington, DC.

World Economic Forum. 2019. *The global risks report* 2019. Geneva.

World Economic Forum. 2020. *The global risks report* 2020. Geneva.

Wu, B. 2012. Evapotranspiration (ET) remote sensing estimation with ETWatch and its application. [online]. [Accessed 12 March 2021]. https://www.fao.org/fileadmin/user_upload/groundwatergovernance/docs/Shijiazhuang/Presentations-PDFs/Day2/PS4_WU_Bingfang_et.pdf

Wu, B., Yan, N., Xiong , J., Bastiaanssen, W.G.M., Zhu, W.& Stein, A. 2012. Validation of ETWatch using field measurements at diverse landscapes: a case study in Hai Basin of China. *Journal of Hydrology*, s436–437: 67– 80.

Wu, B., Jiang, L., Yan, N., Perry, C. & Zeng, H. 2013. Basin-wide evapotranspiration management: concept and practical application in Hai Basin, China. *Agricultural Water Management*, 145: 145–153.

WWAP (United Nations World Water Assessment Programme). 2017. *The United Nations World Water Development Report 2017. Wastewater: the untapped resource.* Paris, UNESCO. (Also available at https://unesdoc.unesco.org/ark:/48223/pf0000247153).

WWAP (World Water Assessment Programme). 2012. *The United Nations World Water Development Report 4. Volume 1. Managing water under uncertainty and risk.* Paris, UNESCO. (Also available at: http://unesdoc.unesco.org/images/0021/002156/215644e. pdf).

WWAP (United Nations World Water Assessment Programme) and UN-Water. 2018. *The United Nations World Water Development Report 2018: Nature-based solutions for water.* Paris, UNESCO. (Also available at https://unesdoc.unesco.org/ark:/48223/pf0000261424).

Xiong, J., Wu, B.F., Liu, S.F., Yan, N.N. & Wu, F.M., 2011. ETWatch: calibration methods. *Journal of Remote Sensing*, 15 (2): 240–254.

Yang, D., Li, C., Hu, H., Lei, Z., Yang, S., Kusuda, T., Koike, T. & Musiake, K. 2004. Analysis of water resources variability in the Yellow River of China during the last half century using historical data. *Water Resources. Research*, 1842, 40.

Yang, Y.T., Roderick, M.L., Zhang, S.., McVicar, T.R. & Donohue, R.J. 2019. Hydrologic implications of vegetation response to elevated CO2 in climate projections. *Nature Climate Change*, 9: 44-48.

Yangwen J. 2011. Groundwater issues and management in the North China Plain. In A.N. Findikakis & K. Sat, eds. *Groundwater management practices*, United States, CC Press. [online]. [Accessed 22 January 2021]. http://www.taylorfrancis.com/books/edit/10.1201/b11062/groundwater-management-practices-angelos-findikakis-kuniaki-sato

Yao, L., Zhao, M., & Xu, T. 2017. China's water-saving irrigation management system: policy, implementation, and challenge. *Sustainability*. 9(12): 2339.

Yeakley, J.A., Ervin, D., Chang, H., Granek, E.F., Dujon, V., Shandas, V. & Brown, D. 2016. Ecosystem services of streams and rivers. In D.J. Gilvear, M.T. Greenwood, M.C. Thoms, & P.J. Wood., eds. *River science: research and management for the 21st Century*, pp. 335-352. UK, Wiley-Blackwell.

Young, M. 2014. Designing water entitlement regimes for an ever-changing and ever-varying future. *Agricultural Water Management* 145, 32–38.

Young, W.J., Anwar, A., Bhatti, T., Borgomeo, E., Davies, S., Garthwaite III, W.R., Gilmont, E.M., Leb, C., Lytton, L., Makin, I. & Saeed, B. 2019. *Pakistan: getting more from water.* Washington, DC, World Bank. (Also available at https://openknowledge.worldbank.org/handle/10986/31160).

Zhang, Y., Chen, K. & Zhu, T. 2018. *Regional and sectoral impacts of water redline policy in China: results from an integrated regional CGE water model.* 2018 Conference, July 28–August 2, 2018, Vancouver, British Columbia 277509, International Association of Agricultural Economists.

Zhang L., Heerink, N., Dries, L. & Shi, X. 2013. Water users associations and irrigation water productivity in Northern China. *Ecological Economics*. 95, 128–136.

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