10 Groundwater for Food Production and Livelihoods – The Nexus with Climate Change and Transboundary Water Management

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Abstract

Groundwater resources in transboundary aquifers may cushion climate change and other impacts of anthropogenic change through irrigation development, which in turn can enhance food security, livelihood benefits and poverty reduction in developing countries. Such resources present significant water reserves that, however, need to undergo critical joint assessment, development and management if they are to provide substantial as well as sustainable scenarios to agricultural and socio-economic development. This chapter explores the nexus between groundwater in shared aquifers, climate change and agricultural growth in the context of Africa, Asia, the Middle East and Latin America and examines the added challenges as well as opportunities that the transboundary setting of these resources may provide in terms of devising lasting solutions. The chapter highlights that both local smaller-scale no-regret as well as larger-scale, strategic adaptation measures that often hinge on integrated surface–groundwater solutions are important. In addition, the socio-economic and institutional aspects, the latter in terms of general international law and specific adapted international agreements as well as bottom-up participatory processes, are critical for attaining success on the ground.

10.1 Introduction

Water management is seen as a key component of climate change adaptation (CCA) in order to enhance societies' resilience against anticipated and emerging impacts (Bates *et al*., 2008). A broadly recognized adaptation strategy involves increasing and managing water storages as a means of offsetting increased variability in precipitation, and consequently in water availability, at various temporal and spatial scales (Taylor, 2009; McCartney and Smakhtin, 2010). Furthermore, improving the extent, performance and sustainability of irrigated agriculture through better agricultural water management is seen as a key adaptation measure in developing regions of the world (Ngigi, 2009).

In this chapter, the role and options for groundwater, and more specifically groundwater in transboundary international settings, are explored in the context of addressing CCA and meeting needs of irrigated agriculture and food security. Groundwater provides reliable, almost ubiquitous, often (albeit not always) renewable water supply, inherent storage and buffering facilities, and hence has been advocated as an

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important and strategic resource in CCA, if managed properly (Clifton *et al*., 2010). While transboundary aquifers (TBAs), defined as those groundwater bodies spanning international boundaries, are increasingly recognized as important around the world (Eckstein, 2011), relatively little attention has been paid to these resources for strategic CCA and agricultural water management. Water management has to increasingly transcend the traditional river basin approach, as promoted by the integrated water resources management (IWRM) paradigm (GWP, 2004), in particular when larger transboundary aquifers play a significant role in the hydrological and ecological systems and/or in water provision, which is often the case in semi-arid and arid areas. Vulnerability and resilience of such TBAs towards climate change may also vary substantially, calling for differentiated and prioritized attention in the context of CCA. Hence, though groundwater's role in CCA and transboundary water resource management is increasingly acknowledged, their nexus with agriculture and food production has hitherto received little attention, and this chapter intends to bridge this gap.

The chapter sets out by giving a short inventory of the global extent, diversity and significance of TBAs. Then, the role, options and limits of groundwater in adaptation are briefly discussed, giving a summary of the comparative characteristics and added advantages of groundwater for managed storage, relative to that of, or in combination with, surface water as well as a list of no-regret options for using groundwater as a component of CCA in agriculture. Finally, the major additional considerations and challenges related to groundwater for irrigated agriculture in TBAs under climate change prospects are highlighted, devising a simple typology, including examples of particular TBAs, as a framework for developing best development and management solutions. The chapter focuses geographically on developing continental regions of the world with larger TBAs: Asia, Africa, the Middle East and Latin America.

As in prehistoric times, where early settled agrarian civilizations clustered around rivers, deltas and springs that provided reliable and easily accessible water resources, future human development may increasingly concentrate around significant groundwater resources and aquifer systems, some of them of international dimensions, that provide reliable, replenishable, protected and manageable water reserves linked to harvestable rainwater, surface water, wastewater streams and manufactured (e.g. desalinated) water. A significant premise here is that underground natural or enhanced recharge of fresh water presents a very favourable means of limiting excessive losses to evaporation under a warmer climate while augmenting stable supplies. The positive relation between the value of land and groundwater availability is increasingly acknowledged, especially when the resources decline (Lee and Bagley, 1972) or is in high demand in less-developed regions (Woodhouse and Ganho, 2011).

Groundwater plays and most likely will continue to play an increasingly important role in meeting global water supply and storage demands as global temperatures increase, and climate variability challenges existing dependence on more erratic surface-water resources. Today, more than one-third of the global population is dependent on groundwater for their domestic supply (Morris *et al*., 2003; Döll *et al*., 2012), while about 40% of all irrigated land is supplied by groundwater (Döll *et al*., 2012; Foster and Shah, 2012), most critically in arid and semi-arid regions. These figures have been increasing unprecedentedly over the latter part of the last and into this century as access to, and awareness of, groundwater in development has accelerated, providing profound development benefits in terms of agricultural livelihoods, food production and productivity increases, water security and improved public health (Shah *et al*., 2007; Carter and Bevan, 2008; Gun, 2012).

Yet, today it is estimated that 18% of global groundwater-based irrigation is unsustainable, i.e. that it derives from depleting aquifers, where groundwater is utilized at rates faster than their replenishment (Wada *et al*., 2012a). Hence, the challenge presently relates to moderating existing groundwater demands through efficiency gains, enhancing replenishment through purposeful management wherever possible, cautious development of new sources in still undeveloped regions, optimizing and diversifying multiple sources (including surface water), preserving valuable groundwater-dependent terrestrial and aquatic ecosystems, all in the context of larger uncertainty, variability and risks prescribed by climate change as well as in a globally increasingly interdependent community.

10.2 Transboundary Aquifers

Transboundary aquifers are relatively well-defined units of geological and associated groundwater systems that lie partially in more than one sovereign state[1] (Stephan, 2009). They are delineated, based on geological and hydraulic characteristics and boundaries. Because of larger uncertainties related to the characterization and delineation of these underground water-bearing units compared to international river basins, the definition of these systems also depends on a general agreement between aquifer-sharing states of the transboundary nature of the aquifer. While many TBAs may be (partly) hydraulically connected to rivers or other surface water bodies (e.g. lakes) this is not always the case, and more often than not, these systems are not geographically coincident with river basins (see Fig. 10.1 for the example of Africa). This mismatch between geographic extent of the surface and groundwater systems implies complication in relation to defining best management units for integrated and transboundary water resources' management (Schmeier, 2010; Altchenko and Villholth, 2013).

Transboundary groundwater resources are gaining enhanced attention from water developers as well as from the international research community and increasingly also from national and international policy makers due to increasing stress on available water resources (Aureli and Eckstein, 2011). With increasing attention, the knowledge of acknowledged TBAs increases and the number of newly identified and agreed TBAs expands (IGRAC, 2015). At present, a global inventory reveals the existence of 592 TBAs (IGRAC, 2015). This surpasses the present number of international river basins, which stands at 263 (Cooley *et al*., 2009), documenting that these resources are indeed of global as well as of local significance. Impacts of negligence of recognizing the transboundary nature of these systems partly resemble those for international rivers, in terms of water quantity-sharing aspects as well as potential water quality issues.[2] When the surface water and groundwater systems are linked, these problems become interrelated.[3] However, certain management aspects are particular to the TBAs (and aquifers more broadly) and relate to their invisible, open-source and vulnerable nature (Table 10.1). These aspects need to be given much more attention in sustainable management and protection of TBAs as compared to internationally shared river systems. On the other hand, co-aquifer state cooperation on TBAs and associated systems may provide aggregate shared benefits that outweigh the costs and disadvantages of not cooperating (Box 10.1).

TBAs range from smaller, more local aquifers shared between two nations to larger regional contiguous aquifer systems that partially span up to eight states (e.g. the Lake Chad Aquifer Basin in central-western Africa, occupying a land area of $1.3 \times 10^6\,km^2$). The largest TBA in the world is the Guaraní Aquifer in South America with a size of $1.9 \times 10^6\,km^2$ covering parts of Argentina, Brazil, Paraguay and Uruguay. TBAs also vary significantly in geological set-up, depth interval(s) of groundwater occurrence as well as rate and mechanism of replenishment. A complete inventory of global TBAs in terms of these parameters does not exist, but salient data are available from Margat and Gun (2013), IGRAC (2015), and for Africa in Altchenko and Villholth (2013).

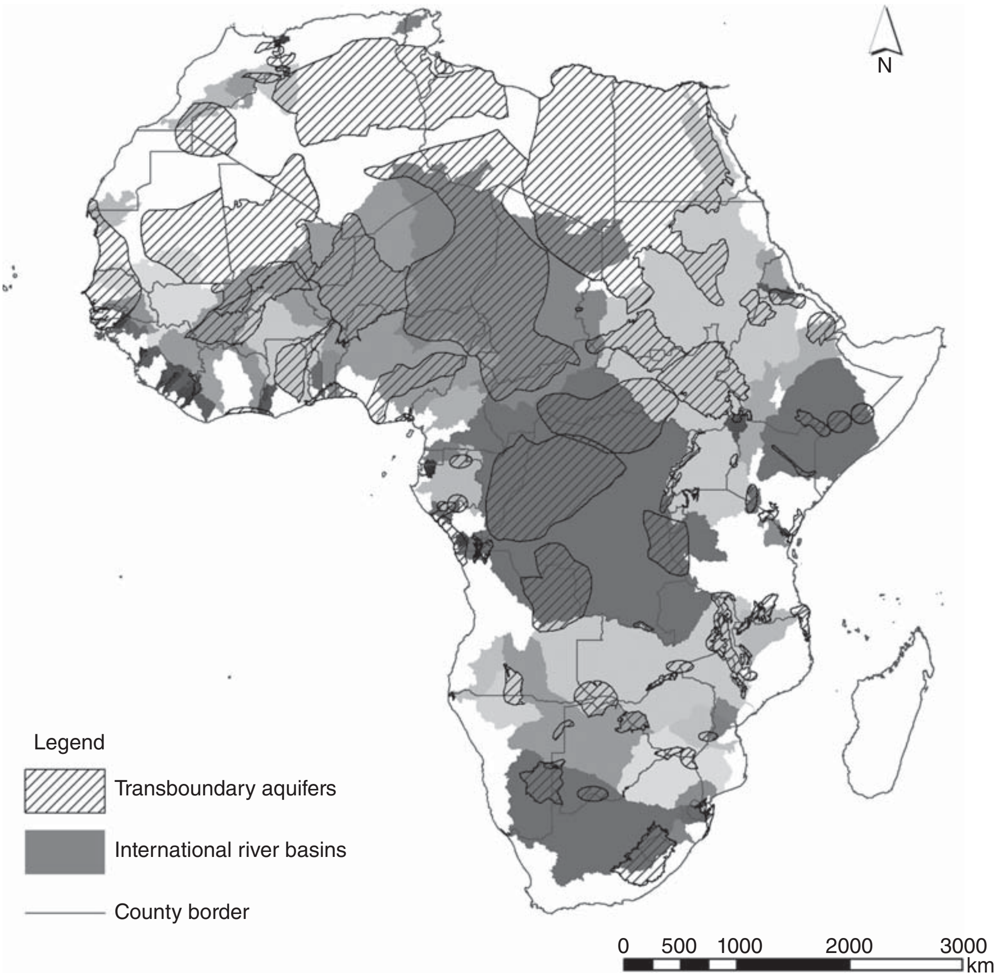

Fig. 10.1. Map of transboundary aquifers of Africa. Depicted are also the international river and lake basins (from IGRAC, 2015). Note that differences in shading weight indicate different river basins.

10.3 Groundwater's Role in Agriculture and Climate Change Adaptation

Groundwater development for agriculture has occurred thanks to the many favourable inherent characteristics of the resource (Table 10.2) and has generally been accompanied by very positive socio-economic transitions (Giordano and Villholth, 2007). Groundwater irrigation has surpassed the role of surface water in terms of acreage, outputs and rural-poverty-alleviating impacts in India (Narayanamoorthy, 2007) and other parts of South Asia, and similar, albeit less pronounced, impacts have been seen in northern China (Foster and Garduño, 2004) and Mexico (World Bank, 2009).

In Africa, particularly south of the Sahara desert, groundwater is presently only contributing minimally to food production, though significant land and hydrological potential exists (Pavelic *et al.*, 2012a). Only

Table 10.1. Particular characteristics of aquifers and implications for management of TBAs.

	Special considerations/provisions needed in TBA management[a]								
Groundwater distinct characteristic	Joint user/use registration, regulation, monitoring and enforcement	Prior notification of development plans to other party	Precautionary principle	Conflict resolution	Stakeholder engagement	Long-term monitoring of resource	Flexibility in conceptual model and clear data-sharing arrangements	Land use and waste regulations	Prioritized protection
Open source	xx				xx				
Invisible and heterogeneous		x	x	x	x	x	x		
Vulnerable to land use impacts					x			xx	x
Slow reacting/delay in response		x	xx	x		xx			
Recharge/discharge is distributed and uneven								x	xx
Boundaries uncertain				x		x	xx		
Climate change impacts uncertain						xx	xx		
Blurred up- and downstream relations			x	x	x	x	xx		

[a]Number of ‘x’s indicates the degree of importance of considerations/provisions.

Box 10.1. Ten arguments for addressing groundwater in transboundary water management

1. Benefits of groundwater (GW) development and management can be equitably shared across borders to avoid climate-induced distress migration and conflicts.
2. GW development and proper management have a lot to do with achieving the Sustainable Development Goals, poverty alleviation, food security, climate change adaptation, and flood and drought mitigation.
3. An integrated and transboundary approach facilitates enhanced understanding of water flows and water balances within the aquifer basin and supports improved delineation of the aquifer, including active and connected surface water (SW) systems.
4. GW impacts across borders may not be obvious without joint long-term monitoring. Costs and results of monitoring can be shared.
5. Impacts of unilateral GW development and use in one member state may affect another.
6. Developing GW in connection with transboundary SW (conjunctive use) may provide a lot of benefits, e.g. floodwaters may be used to replenish GW in overdrawn aquifers; SW pollution may be reduced through riverbank filtration for better drinking water quality, and managed aquifer recharge (MAR) and recovery may support water banking and salinity control.
7. Many terrestrial ecosystems are GW-dependent and cannot be properly managed without acknowledgement of the GW resources.
8. SW issues involve or even have root in GW-related activities and impacts, e.g. water from the river may be lost through GW abstraction in the vicinity of the river.
9. Lake, river, wetland and estuary water quality may be threatened by GW pollution in adjacent upstream aquifer states (mining, intensive agriculture).
10. No-action and lack of transboundary cooperation may result in significant and long-term risks, e.g. haphazard and chaotic exploitation of aquifers with high remediation costs if at all reversible (like certain types of contamination and land subsidence).

about 4% of the cultivated land in sub-Saharan Africa (SSA) is presently irrigated (NEPAD, 2003), leaving large scope for further expansion aiming at protecting farmers against weather fluctuations at various temporal scales through better control of, and access to, water (Ngigi, 2009), while contributing to closing the gap in food production.

The role of groundwater in CCA relates to its reliable and normally drought-resilient character (Table 10.2) implying that the resource can be reliably drawn upon during dry seasons or times of dry spells or drought, when other sources fail. However, besides the characteristics of the resource itself, the effective buffering capacity of groundwater resources towards drought hinges critically on the resilience and adaptive capacity of populations and agricultural systems dependent on groundwater. In a simple multifactor assessment, groundwater resources in the regions of South Asia and Africa were considered to be the most vulnerable to climate change, presumably because of the high degree of dependence on groundwater and low adaptive capacity (Clifton *et al.*, 2010). In a similar, but more detailed mapping analysis across the SADC region in southern Africa, Villholth *et al.* (2013) found that the areas underlain by crystalline rock formations, prevalent in SSA, were among the most vulnerable, because of their relatively low water-holding capacity and poor yields combined with high population densities and high drought risk. Furthermore, the vulnerability of drought of these areas was compounded under a projected climate scenario (Villholth *et al.*, 2013). Such interdisciplinary mapping can be invaluable in pro-active planning of best adaptation measures for drought resilience in these vast transboundary settings.

Besides targeting the most vulnerable areas, drought mitigation through groundwater measures should consider the following principles:

1. Access points (wells) should be drought-proof (located in productive parts of the aquifer, intake level not risking dry-out).
2. Access points should be resilient against additional wear and tear during drought,

Table 10.2. Inherent characteristics of groundwater favouring irrigated agriculture and climate change adaptation.

Groundwater property	Irrigated agriculture	Climate change adaptation
Drought-resilient, reliable	Provides year-round on-demand irrigation, encourages intensification	Bridges seasonal and possibly inter-annual variability
Widespread	Supports rural development	Addresses local vulnerability, away from major water infrastructure
Underground	Increases water productivity	Less storage and conveyance losses from evaporation
Amendable to incremental development	Potentially pro-poor. Can be developed by individual farmers or small groups	Requires small investments and lends rapid response
Versatility[a]	Addresses gender needs to diversified water use purposes	Can address several vulnerabilities and water needs
Flexibility[b]	Can help control waterlogging and salinization	Can combine with other sources to optimize storage and increase overall resilience. Can address both drought and floods

[a] Groundwater can be developed for various (multiple) uses in rural areas.
[b] Groundwater can be combined with other sources (conjunctive use) to optimize overall use.

and easily maintainable in distant rural areas.

3. Dedicated drought wells may be reserved for emergency situations.

Importantly, degradation of groundwater resources, due to climate change, prolonged drought or human impacts, will increase the vulnerability of populations dependent on them, ultimately reducing their capacity to shield deficits in other water resources and hence undermining water security for domestic and livelihood purposes. This underpins the critical importance of proper groundwater management.

While basic water supply takes precedence during drought, adapting livelihoods and ensuring availability and accessibility of productive water during projected scenarios of increased rainfall variability are also critical. Since irrigated agriculture serves several development goals, in terms of food security, livelihoods and reduction in rural poverty, developing it wisely as a component of a CCA strategy is further justified. Some pointers as to how to address development and management of groundwater for irrigation and CCA can be put forward. These will be discussed briefly below.

10.4 Ensuring Access to the Poorest

10.4.1 Lowering costs

The major stumbling block for poor farmers to access groundwater in SSA and possibly in other regions of the world, where multidimensional potentials exist, as in parts of the Greater Mekong Region (Johnston *et al.*, 2010), is the requirement for physically drilling holes to the resource and to lift the water to the surface. While progress is seen in terms of declining prices for well drilling and acquiring mechanical pumps along with a developing demand and supply, it is also evident that most smallholder farmers still avail themselves of very rudimentary and labour-intensive means of extracting and lifting groundwater, including manual digging and hand-lifting and watering with buckets, which in prosperous areas limit the accessible resources and hence the level of development (Namara *et al.*, 2011). Where public investment supplies groundwater irrigation facilities, benefits do not necessarily reach the poorest segments. Hence, a critical policy is to support local cost-effective pump and drilling manufacturing, markets and associated services (Abric *et al.*, 2011), ensuring expansion and coverage in rural areas in order to decrease investment and transaction costs. It also entails instituting and supporting small farmers in obtaining access to both import and tax-waiver systems for pumps for irrigation equipment. Finally, well-targeted subsidies, potentially with feasible payback schemes to increase cost recovery and long-term financial viability of public funds and micro-credit services (Nkonya *et al*., 2010) should be looked into more closely.

10.4.2 Pump and groundwater markets

Previous experience from Asia indicates that the share of farmers, and particularly of the poorest segments benefiting from groundwater, increases due to spontaneous and informal groundwater and pump rental markets (Villholth *et al*., 2009). Generally, wealthier farmers individually owning pumps and wells sell water (or rather the service of water provision) and/or rent pumps to other farmers without these assets, thereby increasing overall access and income generation. Pump rentals have also been popular in Africa, while groundwater markets have not. While not presently significant, these institutions may spontaneously develop in SSA as groundwater-based irrigation proliferates among smallholder farmers.

10.4.3 Multiple use systems

Rather than dedicated and separate domestic and irrigation infrastructure, multipurpose systems, catering to the various water needs of rural households need to be further considered. It has been observed (Calow *et al*., 2009) that domestic water points are often used for productive uses, e.g. in garden irrigation, livestock-rearing, brewing and brick-making, and that this increases the resilience of the households, even though water points are traditionally not designed with multiple uses in mind. Hence, adapting groundwater irrigation structures and their location with these realities in mind better serves the needs of the poorest and female farmers (Koppen *et al*., 2009). However, the largest challenge confronted in taking this forward is the fact that the sectors for water supply and agriculture remain institutionally and functionally detached. Ensuring basic domestic water supply should, in any case, be first priority in underserved areas, and should not be compromised by poorly planned groundwater development for irrigation.

10.4.4 Energy access

As part of lowering entry barriers for smallholder farmers to groundwater irrigated agriculture in SSA, improving rural electrification is critical. Energy from electricity is generally cheaper in SSA compared to other fossil-fuel based sources (Pavelic *et al*., 2012b), but the coverage is the world's lowest at only 24% (UNEP, 2012). Experience from South Asia shows that groundwater-irrigating farmers with access to electricity are generally better off than their counterparts who use diesel or other sources (Villholth *et al*., 2009). While this is partly due to distorting electricity subsidies to the agriculture sector, it shows that groundwater irrigation at a more than subsistence level is linked to better energy provision.

10.5 Ensuring Environmental and Social Sustainability

Globally, irrigation serves about 40% of food production (Wada *et al*., 2012a); about 40% of water for irrigation derives from groundwater (Foster and Shah, 2012), and of the groundwater extracted approximately 67% goes to irrigation (Gun, 2012). Hence, the way groundwater irrigation is managed significantly influences the resource and any potential negative environmental impacts from irrigation. Today, 18% of irrigation demand is derived from aquifers that are overexploited (Wada *et al*., 2012a), with serious and growing socio-economic and environmental implications, especially in certain parts of the world where it has proliferated due to a combination of favourable conditions in terms of push-and-pull factors (Moench, 2003; Kajisa *et al*., 2006; World Bank, 2009). Hence, there is a built-in risk associated with the development of groundwater for irrigation, which is related to some of the same advantageous characteristics of groundwater mentioned in Table 10.2. Management and enforcement of any regulation are hampered by the open-source nature of groundwater, its distributed occurrence with access options for a multitude of dispersed users that are difficult to control in conjunction. A plethora of literature discusses best strategies and options for groundwater management in agriculture (Giordano and Villholth, 2007; Shah, 2009a). Most of this literature focuses on the reactive measures for groundwater management in areas with intensive use and apparent negative impacts. Little attention has been paid to how to pro-actively manage groundwater in areas where the resource is still relatively underdeveloped, ensuring sustainability in terms of lasting poverty alleviation as well as ecosystem and human resilience. In the following sections, a few directions towards this purpose are given realizing that various strategies may serve in the under-developed as well as the over-developed scenario. While these options apply more broadly, they are relevant in the transboundary context in order to optimise use and minimize transboundary effects.

10.5.1 Conjunctive use of groundwater and surface water

Using and managing surface water and groundwater together, or conjunctively, in irrigation, provides options for better overall control, efficiency in use and productivity of both quality and quantity aspects of the resources (Evans and Evans, 2012). Groundwater irrigation may complement canal irrigation in areas where the groundwater table is rising and waterlogging and concomitant salinization is causing decreasing performance. This was evidenced in parts of the transboundary Indus plains (mostly Pakistan) where government drilling schemes helped alleviate waterlogging problems in the 1960s (Scanlon *et al*., 2007). This may be a viable option in parts of India where areas of waterlogging still persist in the midst of larger areas of groundwater depletion (Foster and van Steenbergen, 2011). Similarly, options exist in existing canal irrigation schemes with waterlogging problems in Africa (Ojo *et al*., 2011) as well as in suburban areas, where groundwater levels are increasing due to unintentional water leakage or intentional wastewater recharge (Foster *et al*., 2010). Often, in canal irrigation areas, conjunctive use of groundwater develops spontaneously, partly as a coping mechanism of farmers to get reliable access to water in poorly managed canal irrigation schemes (Foster and van Steenbergen, 2011). However, the challenge is to rather plan, better design and optimize the schemes for conjunctive use, ensuring that headwater as well as tail-water users and areas are reliably served, not compromised by saltwater threats.

Similarly, critically evaluated surface-water transfers may help support irrigation in groundwater-depleted areas, as is seen, for example, in China, where huge interstate transfer schemes supply water from the water-rich south to the relatively water-deficient north, and transferred water is used for irrigation in the form of waste water after serving urban demands (Shu *et al*., 2012).

In summary, water sources need to be increasingly diversified and integrated, and management needs to reflect this. Similarly, planned integrated conjunctive use may be a better solution than swaying back and forth from primarily depending on one or the other resource as seen in some places around the world (Clifton *et al*., 2010). Another critical aspect of conjunctive use is that it tends to conserve on overall energy use (Shah, 2009b).

10.5.2 Local management of irrigation

As mentioned, groundwater management is still poorly conceived when it comes to tackling use in agriculture. Basically, an institutional top-down and a bottom-up approach is proposed in addition to more indirect measures (Giordano, 2009) linked, for example, to food, agriculture, energy, health and nature-conservation policies (Sekhri, 2012). In developing countries, the top-down, direct approach to groundwater management, involving user rights and economic instruments like water tariffs, is less tractable and effective, while the more indirect approaches, particularly the link to energy, promises to have some traction (Shah *et al*., 2012).

The bottom-up approach, where community involvement and mobilization are required to manage local groundwater resources use, deserves further testing, particularly in connection with the more indirect measures at the national and even the international level (Wijnen *et al*., 2012). These measures, which involve collective rule-setting and enforcement, e.g. in terms of timing of groundwater pumping, well spacing, crop choices, compulsory recharge structures and water-saving irrigation infrastructure, monitoring of the resource, etc. seem to work best if some of the following conditions prevail: existence of strong social capital, relatively homogeneous population groups, strong visionary local leadership to ensure motivation and compliance, the resource being relatively well defined and responding evidently and rapidly to demand management, the regulations are easily monitored, and the number of stakeholders are relatively limited. The challenge is to develop self-motivated and sustainable processes that do not need continued inputs and subsidies (Wijnen *et al*., 2012), even in transboundary settings.

10.6 Managed Aquifer Recharge and Storage

A continuum of surface and subsurface options for water storage is available, each solution with specific characteristics and options for management (McCartney and Smakhtin, 2010). Managing underground water is a critical component in the context of water scarcity and climate change (Clifton *et al*., 2010), though traditionally it has received less attention (Taylor, 2009) relative to surface water storage. Though some similarities exist between groundwater storage and surface water storage options (typically dams), groundwater storage presents inherent features that make management significantly different from management of a large impounded reservoir (Table 10.3).

Managing groundwater storage entails the co-management of recharge as well as discharge processes (Dillon *et al*., 2009), with recharge typically being the most amenable component to manipulate, through various so-called managed aquifer recharge approaches (MAR). In irrigated agriculture, the objectives of MAR typically relate to offsetting abstraction in excess of natural replenishment, the levelling out of seasonal or inter-annual variations in storage, or the expansion of areas of crop production. In most cases, transfer of source water, e.g. from surface water, rainwater or wastewater is involved. This indicates that MAR is just as much a matter of surface water management, or rather integrated management of multiple sources and conjunctive use, as one of only groundwater.

Managing the discharge of groundwater as a part of controlling storage volumes and groundwater levels becomes important in waterlogged surface irrigation schemes, as previously discussed. It is also relevant in planned MAR, where the discharge of groundwater and associated drawdown of water table levels needs to be synchronized relative to the recharge, which is typically governed by seasonal availability of source water.

While MAR and managed groundwater storage present multiple options and potential benefits, numerous considerations need to be taken into account. It needs to be cost-effective and adapted to the local context. It needs to be anchored in institutional set-ups in order to level social inequity in water access rather than exacerbate it. Finally, various environmental impacts (upstream/downstream) need to be closely examined, both in terms of water quantity and quality

Table 10.3. Comparison between groundwater and surface water as manageable water storage and supply, through MAR and large dam reservoirs, respectively.

	Groundwater	Surface water
Storage volume and flux determination	Difficult	Easy
Physical impoundment	Difficult	Easy
Storage regulation	More difficult	Easy
Discharge/abstraction and allocation regulation	More difficult, open source, users ill-defined	Easy, users well-defined
Water source for storage	Needs to be collected and directed to recharge sites, e.g. from storm water, rainwater, floodwater, refuse water	Immediately available from upstream river
Reliability of water source	Depends on the source	Depends on climate and watershed management
Uncertainty in replenishment rate if water source available	High due to clogging phenomena	None
Evaporation losses	Low	High
Drought vulnerability	Lower, due to less evapotranspiration losses and retardation between inflows and outflows	Higher, due to evapotranspiration losses and limited accretion during drought
Drought impacts	Shallow wells and poorest communities hit first	Multiple water uses may be impaired, including hydropower
Drought mitigation options	Can drill/use deeper wells for interim relief	Can temporarily compromise on environmental flow releases
Flood vulnerability	Low if storage managed and located optimally; localized vulnerability in low-lying/discharge zones	Low if storage operated optimally; localized vulnerability along downstream reaches
Flood impacts above storage and detention capacity	Slow-emerging water level rises locally	Can be catastrophic downstream
Flood mitigation options	Floodwater diversions from infiltration/ recharge sites, evacuation of vulnerable areas; can prioritize abstraction ahead of crisis	Flood modelling, flood warning, pre-flood releases, evacuation of vulnerable areas
Risk of waterborne diseases	Low	High
Life span	High; depends on clogging control and water quality control	Low; depends on siltation
Water quality	Depends on watershed management, land use and source water for MAR	Depends on watershed management
Catering for environmental flow and storage requirements	More difficult due to releases dependent on level of groundwater	Easy through informed release schemes
Carbon footprint of water use	Depends on depth of pumping and pump efficiency	Depends on need and extent of non-gravity conveyance

issues. Significant experiences with MAR exist from India (Sakthivadivel, 2007) and other developing countries (Dillon *et al*., 2013), and though the level of documentation of effectiveness and socio-economic impacts is improving, the knowledge of environmental impacts is still limited.

MAR is often brought forward as a panacea for addressing water scarcity and CCA (Clifton *et al*., 2010), even in the transboundary setting (Puri and Struckmeier, 2010), and also for stabilizing depleting aquifers (Shah, 2009b). However, it needs a lot more detailed examination and actual testing, as well as adaptation to developmental contexts (Dillon *et al*., 2009). Supporting storage recovery in seriously depleting aquifers through MAR alone seems unrealistic in many cases (Dillon *et al*., 2013). A multitude of actions, including demand management, soil and catchment management, and even partly curtailing irrigation may be needed (Moench, 2003). However, the role of MAR will become increasingly important as water demand increases and the impacts of climate change and variability become more apparent.

10.7 Climate Change Impact on Groundwater

Despite the fourth assessment report of the Intergovernmental Panel on Climate Change recognizing the deficiency in our understanding of impacts of climate change on groundwater (Bates *et al*., 2008), recent work is slowly showing progress (Taylor *et al*., 2013a). The challenges are related to limited long-term monitoring of groundwater resources, as well as imperfect understanding of the climatic changes and impacts on fundamental processes like groundwater recharge. Generally, impacts on groundwater systems are subdued and delayed compared to those on surface water systems.

Precipitation changes may affect recharge in non-linear ways (Clifton *et al*., 2010), and impacts may depend more on variability of the rainfall and short-term intensity than on longer-term averages (Taylor *et al*., 2013a). Infiltration and net percolation to groundwater are also governed by soil surface, geological, vegetation and atmospheric conditions and changes therein, whether driven by climatic changes or otherwise. Responses (direction and extent) will depend on the relative strength of these factors in various regions. There seems to be consensus on the projection of increase in number and/or intensity of extreme rainfall events globally (Bates *et al*., 2008; Gregersen *et al*., 2013). However, large uncertainty pertains to impacts of this on recharge in various regions. Research indicates that recharge may shift to more episodic events, driven by more intense and extreme rainfall events, especially in the warmer climates. While warming serves to increase evapotranspiration demand thereby limiting excess water for recharge, more intense rainfall would be likely to more than overcome this. Larger infiltration and recharge as a response to higher rainfall intensity in various climates may also be promoted by preferential flow processes, governed by pedological and geological conditions (Villholth *et al*., 1998). In contrast, other reports suggest increased surface runoff and/or evapotranspiration and, as a net outcome, overall decreased recharge resulting from higher-intensity rainfall (Dourte *et al*., 2013). In cooler climates, seasonal recharge transitions seem to be shaped by earlier and more intense snowmelt in the spring, which increases recharge, and possibly less recharge due to declining effective rainfall (precipitation minus evapotranspiration) during summer (Okkonen *et al*., 2010).

Many reports highlight the significance of concurrent human and climate-change-induced impacts on groundwater resources (e.g. Treidel *et al*., 2012). There is an expected compounded indirect impact of higher overall water demand and increased reliance on groundwater in a warmer and more unpredictable climate (Chen *et al*., 2004). This indicates a need for addressing both types of forcings, human as well as climate change, which are collectively set to increase in the future. Land-use changes, often associated with new land cultivation, are significant drivers of hydrological change and have also been shown to have comparable or overriding impacts on groundwater resources relative to that of climate change and variability (Scanlon *et al*., 2006). Increasing irrigation water demand due to higher evapotranspiration rates and the need for overcoming uncertainty and variability in rainfall and hence greater risk in rainfed agriculture, may result in increasing recharge and groundwater levels, due to irrigation return flows (Toews and Allen, 2009; Döll *et al*., 2012), or conversely in increasing net storage depletion and falling groundwater levels (Shu *et al*., 2012), depending on the primary source of irrigation water, whether from surface water or groundwater, respectively.

Projecting climate change impacts on groundwater systems is associated with limited confidence, due to uncertainties in global circulation models (GCMs) propagated to uncertainties in nested regional or smaller-scale hydrological models (Zhou *et al*., 2010), particularly pertaining to precipitation in the former and recharge in the latter. Outcomes are often highly variable and even partly conflicting when ensembles of GCMs and climate scenarios are applied. Furthermore, many larger-scale hydrological models use simplified assumptions related to groundwater-relevant processes (Holman *et al*., 2011; Taylor *et al*., 2013b), implying critical uncertainty in quantitatively projecting climate change impacts on groundwater storage and availability. Often-cited global-scale modelling of climate change impact on groundwater (Döll, 2009) assumes groundwater replenishment deriving only from diffuse recharge and disregards focused recharge (from perennial and ephemeral surface water bodies) as well as increased short-term (less than monthly) rainfall variability, the effect of both of which may be critical. Enhancing long-term groundwater monitoring from land and satellite-based sources is an accompanying significant means to improving our knowledge (Taylor *et al*., 2010).

Impacts of climate change on groundwater quality are generally poorly understood. Adverse groundwater quality impacts of climate change may stem from increased leaching of surface-derived substances in winters in colder climates, similar impacts in warmer climates due to episodic recharge and preferential flow through soils and geological materials, and higher infiltration of contaminated water during flooding events in various climates. Reduced recharge may conversely aggravate groundwater quality through less dilution (Solheim *et al*., 2010). Great concern relates to projected sea-level rise and increased intrusion of salt water in freshwater coastal areas and on smaller islands (Bates *et al*., 2008; Villholth, 2013). This will be exacerbated or overruled by intensified groundwater pumping (Ferguson and Gleeson, 2012). It could also, *ceteris paribus*, be counterbalanced by natural groundwater-level lifting processes (Chang *et al*., 2011). Irrespective, as stated by Custodio (2004), research needs to be careful in attributing salinity increases in coastal areas directly to sea-level rise as salinity may be derived from a complex, sometimes interrelated array of sources, such as innate geological salinity, urban pollution, pumping-induced ingress of salt water, irrigation-derived salinity, etc. Interestingly, groundwater depletion may augment global sea-level rise (Wada *et al*., 2012b), indicating the complex interrelations between groundwater and climate change.

Transboundary aquifers as a sub-set of all aquifers will be subject to similar climate-change impacts globally, and the study of these and potential CCA options are discussed in the next section.

10.8 The Potential Role of Transboundary Aquifers in Climate Change Adaptation

Transboundary aquifers across the globe are diverse in many respects and their role in CCA will vary accordingly. Multiple criteria can be set up for their potential role, for example, in terms of lateral extent, stored and presently recurrently replenished water volumes, depth of access, water quality, countries sharing, present degree of development and pressures. Some TBAs are still relatively undeveloped, presenting significant opportunities for further joint development and adaptive use, while others are already stressed from existing human development. As an example of the first, the Ohangwena freshwater aquifer between Angola and Namibia (part of the Cuvelai-Etosha Basin) is presently being investigated for potential exploitation in the border region between the two countries, including for small-scale irrigation (Christelis *et al*., 2012). Development of this aquifer could supplement supply from international surface water transfer from Angola to Namibia and support further economic development. However, the recharge status of the aquifer (whether presently recharged and if so how much) still needs to be assessed. An example of an over-exploited TBA is the Santa Cruz aquifer between Mexico and the USA, which presents similar characteristics as other over-developed aquifers shared between the two countries (Scott *et al*., 2012). However, other TBAs exhibit partial development in only parts of the aquifer, with huge potential in others, like the great Guaraní aquifer in South America, shared between four nations (OAS, 2009). Similarly, in the Ganges Basin, shared between India, Nepal and Bangladesh (and possibly Bhutan and Burma) groundwater development varies substantially across the basin. Generally, the degree of development and interest in the TBAs increase from humid to arid areas and with level of human development. Large and significant TBAs (like the Nubian Sandstone aquifer and the North Western Sahara aquifer) located in arid regions are non-renewable, giving rise to special challenges in terms of overall sustainable management (Foster and Loucks, 2006).

The arguments for focusing on TBAs in terms of CCA include the following aspects:

1. Climate change is transboundary, and adaptation measures and related water governance structures need to reflect this.
2. There is increasing dependence upon groundwater resources and many exploited aquifers are transboundary with potential transboundary implications (i.e. abstraction in one country affects another).
3. Many transboundary river basins include or intersect with TBAs and the surface water and groundwater resources are hydraulically interlinked.
4. Use and management of groundwater, in combination with surface water, offers more sustainable solutions than the current predominant focus on surface water in transboundary water management.
5. Joint development and management of the TBAs could lead to more equitable and sustainable agricultural development and regional stability and integration.

These aspects are relevant in addition to the more general points brought forward on the role of groundwater in CCA in Section 10.3. Ensuring equitable development of groundwater and food production and sharing of benefits across borders may alleviate impacts of climate change and extremes and prevent mass migration during droughts (Calow and MacDonald, 2009; Namara *et al*., 2011). Likewise, conjunctive use of groundwater and surface water for agriculture and other purposes may limit the need for large transfer schemes across borders, if water can be drafted from groundwater with its in-built transmission capabilities rather than through relatively costly dam and pipeline/canal systems. Better management of wet-season river flows or floodwaters via MAR in transboundary river basins may benefit from joint management of the storages (in impoundments and aquifers) across the borders, as illustrated in the case from the Fergana Valley in the Syr Darya River Basin, now a transboundary basin spanning Kyrgyzstan, Tajikistan, Uzbekistan and Kazakhstan (Karimov *et al*., 2009). In this case, storing underground the excessive winter releases from upstream dams necessary for electricity production could provide reliable irrigation water sources in the summer and could prevent waterlogging and salinity problems and flooding risk downstream. Large opportunities for CCA and better aquifer management will be foregone if such transboundary solutions are not sought and optimized. In heavily exploited transboundary aquifers (like the Indus, the US–Mexican aquifers and many aquifers in the Middle East) reducing stress is the key, and the options for expanding irrigation are limited and entail more innovative approaches, like reusing or using wastewater or poorer-quality groundwater infeasible for human consumption, while optimizing not only production with limited resources but use across the borders (Table 10.4).

Small-scale irrigation from TBAs may be considered 'no regret'[4] adaptation measures in many transboundary regions. Though solutions will vary from context to context, some options that may serve to enhance resilience in irrigation and agricultural development are listed in Box 10.2. In fact, many of these 'no regrets' adaptations can be implemented in areas where water

Table 10.4. Best approaches for CCA in TBAs depending on development level and degree of current natural replenishment.

Undeveloped (replenished)	Over-developed (replenished)	Non-renewable (over-developed or not)
Floodwater management, proper drainage, conjunctive use	Conjunctive use to optimize resource use	Equitable use across countries, sectors and users. Protection of domestic users
Simple MAR to capture and control floodwater	MAR from recycled or floodwater	Exit strategies entailing alternative water resources and/or livelihoods
Conjunctive use to avoid waterlogging	Opportunistic small-scale use	Use of renewable energy and efficient pumps for extraction
Intensifying crop-cultivation	Groundwater demand management	Groundwater demand management
Protection of TBA and groundwater-dependent ecosystems	Growing high-value crops, drought-resistant crops and peri-urban cropping	Growing high-value crops, shifting cultivation to non-depleted areas (outside the aquifer) and/or increase imports of food
Drawing down aquifers to enable renewed seasonal storage	Protection of TBA, recharge zones and groundwater-dependent ecosystems	
	Shifting to efficient rainfed agriculture, fallow conditions and urban livelihoods	
	Use of renewable energy and efficient pumps for extraction	
Jointly collect data on shared aquifers	Jointly collect data on shared aquifers	Jointly collect data on shared aquifers
Ensure binding international water agreements between aquifer states	Ensure binding international water agreements between aquifer states	Ensure binding international water agreements between aquifer states
Example:	Example:	Nubian Sandstone Aquifer (Chad, Egypt, Libya, Sudan) (Foster and Loucks, 2006)
Lower Ganges Basin (India, Nepal, Bangladesh) (Villholth *et al*., 2009; Sharma *et al*., 2011)	High Plains aquifer (various states in the USA) (Scanlon *et al*., 2012)	
Guaraní Aquifer (Argentina, Brazil, Paraguay and Uruguay) (OAS, 2009)	Santa Clara Aquifer (USA, Mexico) (Scott *et al*., 2012), the transboundary aquifers underlying Euphrates-Tigris rivers (Iran, Iraq, Syria, Turkey) (Voss *et al*., 2013)	

resources are already stressed, regardless of concerns about the uncertainty of climate change projections and assessments of impact on groundwater and surface water resources (Clifton *et al*., 2010). Though these measures have more general applicability, building resilience of poorer communities in and across border regions will significantly enhance regional stability.

These no-regret, smaller-scale adaptation measures should be combined with larger scale, more strategic measures in the TBA areas, related for example to land use, urban development and water quality protection, which will impact the overall groundwater resource.

In Table 10.4, a simple typology for TBAs in terms of CCA approaches in agriculture is given. The only distinguishing feature is the level of development, though others, such as present climate and human development, could also be critical. Examples of larger TBAs for the various types are also given.

Box 10.2. No-regret options for using transboundary aquifers in climate change adaptation in agriculture

1. Low-cost, low-technology options for MAR from various sources (rainwater, floodwater).
2. Conjunctive use, including capturing and storing surface water underground when excess is available.
3. Opportunistic small-scale groundwater irrigation for smallholders (including peri-urban), dependent on water availability (Clifton *et al.*, 2010).
4. Including groundwater irrigation in or downstream of surface-water irrigation areas and downstream of surface-water impoundments, to increase benefits and to combat waterlogging and salinization.
5. Manage demand for groundwater in irrigation, e.g. through low-cost micro-irrigation.
6. Adapting to current droughts as a surrogate for adapting to future climate change.
7. Protection of groundwater recharge areas.

Box 10.3. Legal aspects of transboundary aquifers

International policies and agreements on TBAs are emerging. Only 15% of 400 international freshwater treaties presently include explicit provisions for groundwater (Jarvis, 2006), albeit often in a rudimentary manner. A set of guiding draft Articles on the Law of Transboundary Aquifers formulated by the United Nations International Law Commission (Stephan, 2009) exist that complement the presently most widely subscribed-to international law on surface waters, the so-called Convention on the Law of the Non-navigational Uses of International Watercourses, adopted by the UN General Assembly in May 1997 (United Nations, 1997). The draft articles have been developed in retrospect, acknowledging that the surface-water-focused convention was inadequate in addressing transboundary groundwater. The result is the coexistence of two guiding documents, only the latter presently ratified, that do not in isolation or in conjunction sufficiently acknowledge the integrated properties and benefits of both resources (McCaffrey, 2009). Another aspect, which has been brought forward in this context, is that the present international agreements do not adequately account for climate change, variability and adaptation (Cooley *et al.*, 2009).

10.9 Challenges and Recommendations for Climate Change Adaptation and Agricultural Growth in Transboundary Aquifers

Traditionally, TBAs have not attained high-level attention from policy makers, international law (Box 10.3) or from relevant water, agriculture and resource management institutions (Eckstein, 2011). Rather, groundwater presently tends to be managed unilaterally with only emerging trends of global and regional emphasis on the transboundary aspects (e.g. SADC, 2011). Even less significance is accorded these resources in terms of potential for CCA and agricultural growth and particularly food security and poverty reduction in developing regions. Evolving work in these areas seems to arise from increasing recognition of the need in water-stressed regions, like in the case of the non-renewable Nubian Sandstone Aquifer, that now counts on a formal data-sharing[5] agreement and results of a joint transboundary diagnostic (Stephan, 2009; Eckstein, 2011), or due to donor-supported impetus, as in the case of the Guaraní Aquifer system (Villar and Ribeiro, 2012). Notwithstanding these, efforts of UNESCO since the 2000s have been instrumental in raising the research and policy attention to TBAs globally through their International Shared Aquifer Resources Management (ISARM) Project (UNESCO, 2010). The disparity in attention given to different TBAs in the continents considered are to be found in variable attentions from the ISARM project and other donor assistance as well as from the different degrees of water stress and water tension between the aquifer-sharing countries.

International tension related to groundwater is emerging, as in the case of the

Middle East (Eckstein and Eckstein, 2003; Voss *et al*., 2013), demonstrating the significance of these resources for various purposes (including agriculture) and also the need for both bilateral and multilateral negotiations, conflict resolution and agreements on these resources.

Finally, the potential of groundwater, and TBAs as a subset of this, in addressing gaps in food production in prospective areas also needs further attention. The challenge in this respect may lie in the sustainable and equitable development of new resources, ensuring that the resource is not overcommitted, and that development occurs in a fashion that benefits equally all the nations involved and also benefits the poorest segments of the populations. There is a twofold challenge here: (i) the economically stronger nations may drive the development to the detriment of the less developed; and (ii) benefits from agricultural development may accrue mostly to larger-scale commercial farmers.

Africa, and SSA in particular, may epitomize the need and potential for addressing the role of TBAs in climate change and agricultural growth. The region is considered socially vulnerable, a hot-spot for climate change as well as a region with underdeveloped water resources for agriculture, yet a continent with significant sharing of major water resources across borders. In addition, storage capacity of surface water is among the lowest in the world (McCartney and Smakhtin, 2010) and hence focusing more on groundwater and indeed integrated solutions as discussed previously may add to the range of options. In the transboundary sense, groundwater may be more equitable, as aquifer states can share a joint resource without the need for large-scale infrastructure and hence less upstream–downstream controversies. On the other hand, partners will have to come together and create trust and transparency in their individual actions. At the same time, groundwater and also TBA research and advocacy are progressing steadily in SSA, where resources have been mapped to a considerable extent.

However, capacities are limited. To move this agenda forward, there is a need for:

- Addressing the distinct properties of groundwater (Table 10.1) as well as the integrated and conjunctive use potentials of transboundary surface water and groundwater in international water agreements.
- Better understanding of the function, potential, present pressures and vulnerabilities of specific TBAs and how they can sustainably co-benefit the sharing countries.
- Better knowledge of potential climate change impacts on groundwater resources.
- Better knowledge of options and limitations to minimize adverse climate impacts, e.g. MAR.
- Capacity building of institutions and developers on the potentials and limitations of TBAs in enhancing resilience and food productivity.
- Further transboundary cooperation and dialogue with an increased focus on the role of groundwater in agriculture.
- Simultaneous bottom-up and top-down approaches to TBA management.

Proper groundwater management cannot be achieved without the active involvement of users and stakeholders, as access and impacts are often local and/or diffuse and dispersed over the extent of the aquifer area. Conversely, grasping the transboundary significance and seizing the potentials in a long-term sustainable fashion without compromising dependent ecosystems and populations will most often require involvement and commitment at the highest national and international level.

10.10 Conclusions

Groundwater often takes second seat in development policies and strategies, especially related to agriculture and transboundary water collaboration, but it may well be a decisive resource for CCA and social and environmental resilience in many settings. This chapter advocates for increased attention to the role that TBAs can play in addressing climate change resilience, water and food security, and regional integration and cooperation. However, this requires increased emphasis, capacity development and awareness-raising at all levels to harness the options available through integrated solutions. The ability to manage groundwater will affect overall development and adaptation performance and outcomes. While on the one hand groundwater dependence is set to increase partly because of its storage properties and climate variability resilience, on the other, mal-management of groundwater entails loss of exactly that property of the resource.

Notes

1 The definition of TBAs does not imply that groundwater resources in border regions outside of TBAs do not exist or manifest similar properties as TBAs. However, the extent and significance of such resources are presently considered of limited transboundary importance or their transboundary extent has not been identified or acknowledged.

2 Groundwater abstraction in one country may influence groundwater flow and availability in another country. Groundwater pollution in one country may spread through the aquifer to an adjacent country.

3 For example, groundwater pumping in riparian zones of one country may affect river flows downstream in an adjacent country. Likewise, pollution of aquifers in one country may enter an adjacent country, by way of base flow to an international river.

4 Actions that are justifiable from economic, social and environmental perspectives whether climate change takes place or not (Siegel and Jorgensen, 2011).

5 Limited experience with actual and quantitative water sharing of TBAs exists at present (Eckstein, 2011).

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