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CGIAR Research Program on Water, Land and Ecosystems (WLE)

GROUNDWATER AND ECOSYSTEM SERVICES

A FRAMEWORK FOR MANAGING SMALLHOLDER GROUNDWATER-DEPENDENT AGRARIAN SOCIO-ECOLOGIES - APPLYING AN ECOSYSTEM SERVICES AND RESILIENCE APPROACH

IN PARTNERSHIP WITH:

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'We must not kill the goose (groundwater) that lays the golden eggs'

Mihir Shah
WLE Steering Committee

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INTRODUCTION

Unprecedented expansion of groundwater use for irrigation has underpinned the agrarian transformation in South and East Asia and other parts of the world, like the Middle East, northern Africa and central Asia, over the past five decades (Shah et al., 2007). By promoting intensification and diversification of land use, groundwater development has enhanced socio-economic resilience of smallholder farming systems and increased food security.

At the same time, inexorable pressure on groundwater resources has threatened the sustainability of intensive groundwater use in agriculture (Shah et al., 2007). As a consequence, the environment and the livelihoods dependent on ecosystems linked to groundwater have been compromised (Danielopol et al., 2003, Moench, 2003). An urgent need is to develop governance and management regimes that can balance the trade-offs between livelihood resilience and socio-economic development on the one hand and ecological resilience of groundwater-dependent agrarian landscapes on the other. In other parts of the world, like in sub-Saharan Africa (Villholth, 2013) and parts of Southeast Asia (Johnston et al., 2009), groundwater irrigation is on the rise among smallholder farmers. To counteract similar trajectories in these regions, it is of paramount importance that previous failures and shortcomings in governance of these types of systems be recognized and accounted for in timely and tailored governance paradigms in order to achieve longer-term sustainability and resilience of these socio-ecologies.

The Water, Land and Ecosystem (WLE) Program has at its core the promotion of sustainable intensification in agriculture through evidence-based research and policy development. Fundamental to the achievement of this goal is the application and uptake of an ecosystem services and resilience-based approach (WLE, 2014). The present Framework Document outlines the WLE conceptual understanding of groundwater-dependent and groundwater-impacting ecosystem services and devises an approach to guide research and policy development related to agrarian socio-ecologies highly dependent on groundwater.

RATIONALE

The rationale for this Framework Document is that groundwater underpins a multitude of ecosystem services on which human societies depend, including and in particular agrarian systems that abstract groundwater for food production and livelihoods in the developing world. Whatever is pumped for irrigation tends to rapidly influence the environment, when above purely smallholder and dispersed small-scale, garden type use. This is because of the large crop and irrigation water demands associated with cropping in the mainly relatively arid environments where groundwater is turned to. On the other hand, the positive livelihood impacts and poverty alleviation implications of utilizing groundwater for sole or supplemental irrigation can be significant in the initial stages of irrigation development, which have been evidenced many places around the world, like in India (Narayanamoorty, 2007, Moench, 2003).

However, groundwater provides many ecosystem services in addition to water pumped for agriculture. Other direct uses of groundwater by people may be compromised when aquifers are over-abstracted for irrigation. One simple example is the lack of drinking water available from groundwater through simple shallow wells (Macdonald et al., 1995). In addition, groundwater supports many ecosystems, including wetlands, rivers, lakes, estuaries, lagoons, springs, oases, and terrestrial systems like forests. People rely on the products and processes of these ecosystems for their health and livelihoods (Brauman at al., 2007). An example of this is people who rely on a freshwater fishery in a stream fed by groundwater. It is clear that compromising the groundwater resource and these ecosystem services undermines not only the agrarian livelihoods, but potentially a vast number of other groundwater-dependent ecosystem services, both the direct uses of groundwater by people and the indirect services provided to humans by groundwater-dependent ecosystems. Some examples of severely stretched groundwater ecosystems and associated agrarian livelihoods are given for China (Foster and Garduño, 2004), India (Anantha and Raju, 2008), Mexico (World Bank, 2009), and Spain (Martinez-Santos et al., 2008).

Concurrently, there is a general shortfall in policy attention to groundwater, either due to under-appreciation of its socio-economic importance, a misunderstanding of its physical inter-linkages with a multitude of other ecosystems on which people depend, or due to the lack of identification and implementation of appropriate solutions to better manage the resource and the human impacts. Hence, researchers have a strong responsibility to articulate facts in understandable language and to co-develop management solutions with relevant stakeholders and decision makers.

Clearly, there is a need to:

- Better understand the inter-linkages between groundwater and various ecosystems and ecosystem services;

- Understand the vulnerability and resilience of groundwater-dependent systems, including the smallholder faming systems, to changes due to groundwater development, and to evaluate how these will be exacerbated by drivers like climate change and land use change;
- Articulate and make transparent the synergies and trade-offs in ecosystem services as a result of groundwater development or other drivers of change, in terms of gains of some services at the expense of others;
- Use the developed understanding for devising solutions that minimize trade-offs in groundwater-dependent ecosystem services, and in particular the negative impacts evident or emerging from intensive groundwater irrigation.

The Framework Document shortly introduces the conceptual framework for groundwater and ecosystem services, with special attention to the agrarian services. This will give a visual understanding of the various ecosystem services associated with groundwater and their spatial and temporal interconnectedness. Secondly, the document will describe some of the negative consequences of not paying due attention to critical ecosystem services provided by groundwater, especially in the quest to optimize farmer crop and economic outputs. Thirdly, overall principles and a couple of examples of applying the ecosystem service and resilience approach to groundwater-dependent socio-ecologies are given. Fourthly, the document proposes a typology for various groundwater-dependent agrarian socio-ecologies from around the world. This is done to clarify some important differences between the various systems and support development of context-appropriate solutions for governance and management. Fifthly, the document presents and discusses various management and adaptation options, exemplified by applied and proven cases from around the world that hopefully can function as guidance and inspiration as we go forward in our goal to address the often unstable approaches to irrigation development based on groundwater services. The sixth section then presents some assessment tools that can be applied in the better understanding of the systems, from hydrogeological, environmental and socio-economic perspectives, and in order to develop management strategies that match the physical, human and governance complexity. The document finishes with a mention of the challenges ahead and associated research needs and questions to be addressed.

The overall objective of the Framework Document is to promote and facilitate the application of ecosystems and resilience-based approaches when dealing with groundwater-dependent agrarian systems in the WLE research portfolio. Secondly, and ultimately, through better research, it is the goal to enhance the integration and uptake of these approaches in wider policy development, thereby complementing integrated land and water management for sustainable social outcomes.

WHAT IS AN ECOSYSTEM SERVICE?

- The benefits provided to people by the products and processes of ecosystems

WHAT IS AN ECOSYSTEM SERVICES AND RESILIENCE APPROACH TO SUSTAINABLE INTENSIFICATION IN AGRICULTURE?

- Aggregate deliberate stakeholder-informed actions for harnessing or restoring ecosystem services for production goals (e.g. increased yields, higher crop-per-drop ratios) while reducing unintended negative impacts on the natural resource base that underpins these services
- Aggregate deliberate actions for improving or retaining resilience, i.e. the ability of a socio-ecological system to undergo change and retain sufficient functionality to continue to support livelihoods through adequate provision of ecosystem services, including quantity, quality, access to and utilisation of food supply, while enabling transformative changes to the system and to the ecosystem services provided or accessed - where this has desirable outcomes, notably poverty alleviation and achieving equitable distribution of service benefits

CONCEPTUAL FRAMEWORK

The core premise of the WLE ecosystem services and resilience framework (WLE, 2014) is that ecosystems are fundamental to human livelihoods and need to be safeguarded to ensure continued productivity and sustainable benefits. We do not want to '*kill the goose that lays the golden eggs*' by using resources indiscriminately, as it will compromise our health, incomes, wellbeing and ultimately our survival. The protection of the environment *per se* is not, however, advocated at the expense of human livelihoods. Rather, safeguarding the environment is predicated for the assurance of long-term sustainability of human benefits from the ecosystem services.

Groundwater has long been the missing link in the ecosystem debate (Tuinstra and van Wensem, 2014). Conceptual sketches for ecosystems services in the World Water Development Report series only included groundwater in 2012 (WWAP, 2012). However, it is increasingly recognized that groundwater underpins and plays a critical role in providing multiple ecosystem services throughout the aquatic, terrestrial, and coastal environment (Klöve et al., 2011; Murray et al., 2006, 2003). In fact, disregarding groundwater increases the risk of mismanagement of land and water resources. Hence, ensuring that groundwater is integrated into any conceptualisation of cause-effect relationships and built into broader water management and spatial planning is paramount. This becomes even more pronounced in societies that increasingly depend on groundwater for human health (e.g. drinking water) and economic development (e.g. agriculture) and where negative impacts can be severe and long-lasting.

Hence, we here present a simple conceptualisation of the ecosystems and their services associated with groundwater (Figure 1). It basically lists and shows the inter-linkages of various ecosystem services associated with groundwater on a landscape scale. What is clear from this is that groundwater both feeds many ecosystem services (like water storage) and also is dependent on others in the catchment (like infiltration and partly purification through the upper soils). Many of these services are linked to the overall flow of freshwater through soils and groundwater systems from recharge to discharge areas. The flow approach also makes it obvious that the curtailing of some of these flows and storages, such as through pumping, or the degradation of the water quality in any part of the system, such as through pollutants, may compromise the services available in other parts of the system. Since groundwater flow is complex, the reality may be much more nuanced than indicated in Figure 1. Basically, flow in groundwater is three-

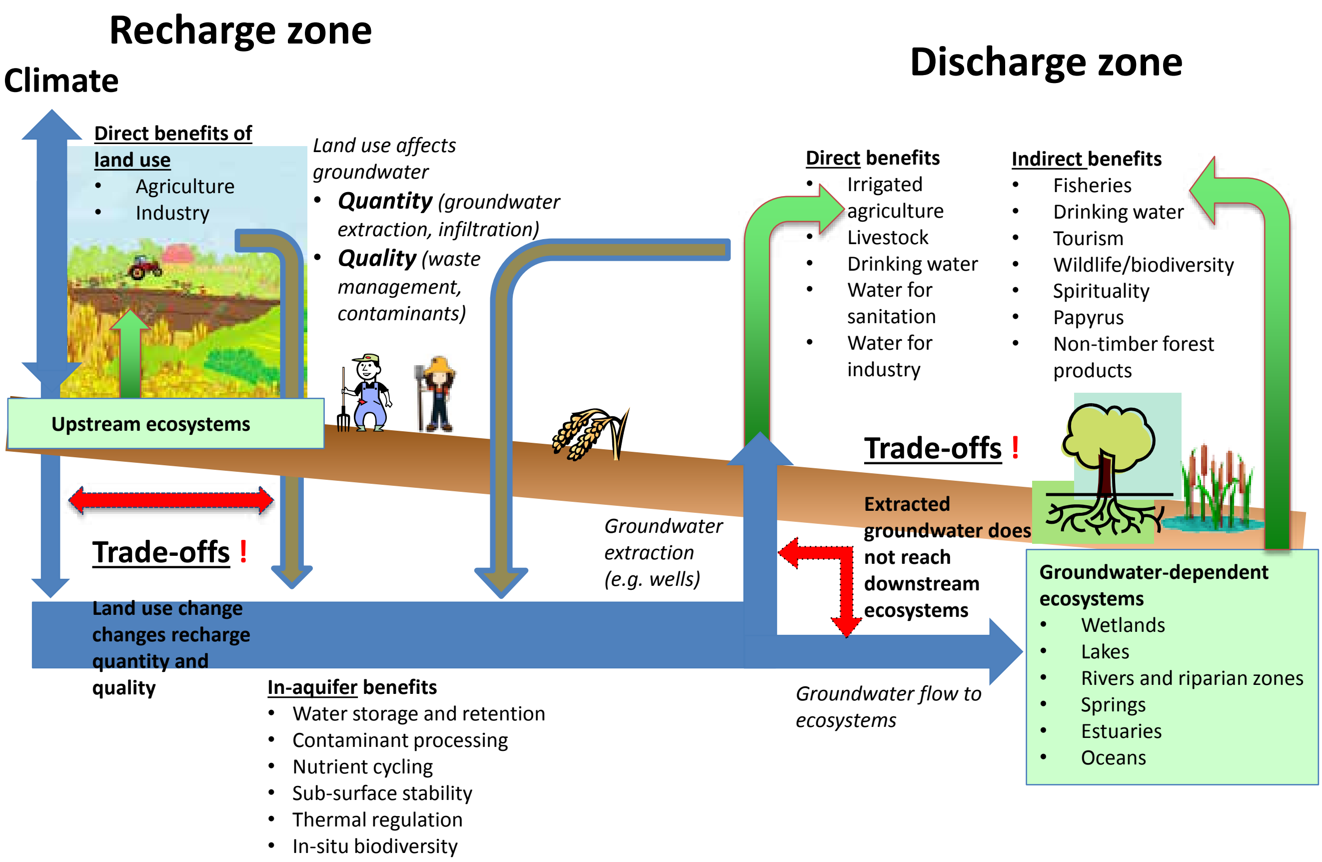

FIGURE 1. Conceptual diagram of the multitude of ecosystem services associated with groundwater over a landscape scale. People benefitting from as well as interacting and influencing ecosystems are implicit throughout

dimensional and it is important to stress that flow can be significantly influenced by heavy pumping; to the extent of changing the apparent and natural 'upstream'- 'downstream' relationships. Groundwater may also be generated in one part of the catchment and appear as surface water in another, while being re-infiltrated to the subsurface again. Often, these complex flow systems are little understood and investigated, but central to the management of the resources (Peñuela-Arévalo and Carrillo-Rivera, 2012).

It is also clear from Figure 1 that groundwater pumping is but one of the multitude of services that groundwater provides or contributes to. The major virtue of this concept is in fact visualizing the interconnectedness of the various services and the way that enhancing or promoting one (like groundwater pumping by one population) may be at the detriment of other more indirect services, e.g. groundwater discharge to streams, wetlands and lakes, which previously may have served as significant sources of livelihoods to other populations. Some impacts may however, also be unintentionally beneficial or synergetic. For example, irrigation may increase terrestrial ecosystems and biodiversity in otherwise very arid areas.

Often, the direct/extractive services, like groundwater abstraction, are favoured indiscriminately to ensure drinking water, food security, local agrarian livelihoods and wider economic growth at the expense of other services, like sub-surface stability or environmental/socially important flows in rivers. While this may serve poverty alleviation in the shorter term, feedback loops from ecosystem degradation may cascade back through these services, thereby reducing well-being, particularly for the poorest members of society (Mayers et al., 2009; Anantha and Raju, 2008). As an example, research indicates that groundwater levels over wider areas or landscapes (and by inference groundwater depletion) affects local and more regional climate (Anyah et al., 2008) (Figure 1). By taking a broader view of the interconnected ecosystem services derived from groundwater, a better understanding and valuing of the various services, the stakeholders involved, the temporal and spatial interrelationships, and potential conflicts are possible. Only through the identification and recognition of the various trade-offs associated with groundwater development, can a 'healthy' balance between direct socio-economic development and preservation of ecosystem services that support livelihoods be achieved. Ultimately, decisions that better account for and balance the various trade-offs can be made.

WHAT ARE TRADE-OFFS?

- A situation in which you must choose between, or balance, two things that are opposite or cannot be had at the same time
- Something that you do not want but must accept in order to have something that you want
- A situation that involves losing one quality or aspect of something in return for gaining another quality or aspect

NEGATIVE IMPACTS OF NEGLECTING AN ECOSYSTEM SERVICE AND RESILIENCE APPROACH TO GROUNDWATER

DISTRIBUTIONAL ISSUES AND SOCIAL INEQUALITIES

In fully understanding the trade-offs associated with ecosystems services, the question of who benefits from the services and who makes the decisions regarding their access and sustained generation becomes important (Leimona et al., 2015; Vira et al., 2012; Luck et al., 2012). Often, poorer populations are heavily dependent on ecosystem services for sustaining their livelihoods, while they have little influence on the decisions related to the development or investment in infrastructure and other interventions that impact on the services. In this context, development becomes guided by the assurance of access and benefits for certain population groups at the detriment of others. Inequity and skewed access (especially gender-related) to e.g. land and agricultural inputs, including groundwater, extends to within poorer communities, (Villholth, 2013; Mapedza et al., n.d.). Furthermore, this skewness may be exacerbated under growing population pressure and also through increased climate pressure, evidenced e.g. by increasing short and long term variability in rainfall patterns. Hence, while there have always been trade-offs associated with developing water and land resources, these predicaments become intensified in a world of more people and more uncertainty. In consequence, the poorer people that may have been reliant on groundwater or other indirect groundwater-related ecosystem services for their livelihoods for generations may be squeezed out, due to e.g. competition from larger farmers who can afford to drill deeper wells or by environmentalists who want to preserve the ecosystems for the sake of conservation or tourism.

The failure to properly regulate groundwater abstraction needs to be tackled in order to overcome distributional issues which arise from social and human inequalities surrounding the access and allocation of groundwater. These distributional issues are often amplified by political drivers, vested interests, skewed land accumulation and ownership, and rent-seeking, which undermine access to the resource for the poor. The framework builds on this knowledge, in trying to address the risks and vulnerability that the poorest farmers are facing.

GROUNDWATER ECOSYSTEM SERVICES DEGRADATION

Groundwater resources and associated ecosystems may be damaged because of intensive groundwater abstraction as well as by other land use changes. This is particularly important for intensive agricultural irrigation development because the volumes abstracted tend to be large (Danielopol et al., 2003). When developing groundwater, it is helpful to remember that this groundwater normally was 'going somewhere' before the development, i.e. to a stream or wetland or the coast. So, by abstracting and using it in crop production, these previous recipients are deprived of this water (Figure 1). In short, groundwater is not a stagnant, stable and infinite resource, which can be drawn on infinitely and without consequences. Removing water has implications, both internally in the groundwater system and in the linked systems that receive or contribute flow from/to groundwater.

A special case is when groundwater occurs as a non-renewable resource under contemporary conditions, often called fossil groundwater. Typically, such groundwater is found in arid areas where groundwater was generated under pre-historic climates. In these cases, groundwater resources may be relatively stagnant, vast, and of particular value, but also concern during development as it will not be replenished, and hence the exploitation is often called groundwater mining. The ecosystem impacts of utilizing such stores may be limited, or could affect distant coastal discharge or discharge to oases. Depletion needs to be associated with a plan for substitution of this resource in the future, artificial/augmented recharge, and optimized use (Foster and Loucks, 2006).

Recharge/Inputs (Figure 1): recharge processes may be affected by land use changes in recharge areas, due to activities such as paving in larger urban areas, erosion and soil degradation, afforestation/deforestation, waste handling, and mining. These processes can reduce (or increase) the total volume of groundwater available (Brauman et al., 2007) and also contaminate existing stores of groundwater, making it unusable. Removing deep-rooted original vegetation and replacing it with rain-fed agricultural crops may decrease levels of evapotranspiration, making groundwater tables rise as seen in the Sahel (Favreau et al., 2009) and in Australia (Allison et al., 1990). In such cases, groundwater irrigation development is a good proposition.

Discharge/outputs: When aquifers are heavily pumped, discharges to terrestrial, aquatic or coastal ecosystems are reduced or changed, potentially causing wetlands to dry up, land to subside or coastal aquifers to become salinized. Water supply for all uses from the aquifer becomes hampered or more costly by increasing depth. Contamination of groundwater can make it unsuitable for direct use or expensive to treat, and it can impair groundwater-dependent ecosystems and reduce the ecosystem services they produce.

AGRICULTURAL IMPACTS ON GROUNDWATER

Agricultural intensification often relies on groundwater, yet the processes of intensification can have negative impacts on the groundwater itself and on related ecosystem services. These negative impacts are related to both the volume of available groundwater and the quality of the groundwater. Some impacts are reversible with time, while others are irreversible. In general, land becomes marginalised with less associated value if the ecosystem services linked to groundwater are degraded.

When groundwater is used for irrigation, it tends to deplete the groundwater resources because water supplied to irrigation is local and drafted from below the fields. Evapotranspiration by the crops represents a consumptive use/loss, and the net result is a removal of water from the system, even when there is return flow from inefficient irrigation systems. When surface water is used for irrigation, by contrast, groundwater is generally net-recharged because surface water represents an external (additional) source of water entering the system, normally with return flow augmenting the groundwater resource. Water logging and salinization is often also linked to improper control of the groundwater interactions during surface water irrigation, i.e. due to improper drainage.

Intensification in agriculture implies increased reliance on agrochemicals such as fertilizers, pesticides and customised seeds. This supports increased economic outputs but also entails risks for groundwater and related ecosystems, particularly from leaching of excess chemicals below the root zone. Such processes may occur in surface water irrigation schemes as well as groundwater irrigation, indicating the intricate inter-linkages between surface and groundwater systems.

THE DIFFICULTY OF TRACKING CHANGES TO GROUNDWATER RESOURCES

Often, the impacts on ecosystem services from groundwater will not manifest themselves immediately. For example, widespread decline of groundwater levels and massive pollution of an aquifer do not occur right away and may take even longer to detect. This is because negative impacts may occur far from the abstraction point/pollution source, and because the flow and transport processes in groundwater are mostly very slow. As a result, lag times of decades can occur between the time that pumping or contamination begins and the time when broader-scale impacts are noticeable. Because of this delay, both the causes and impacts may be difficult to remedy.

Detecting impacts to groundwater resources is additionally complicated because, in many places, the limited capacity of developing countries and in particular of poor farmers means there is little opportunity for formal monitoring of groundwater status. Because of both the nature of groundwater and limited monitoring capacity, it is not always straight forward to assess potential changes in groundwater resources. New low-cost monitoring methods, using mobile phone technology, are emerging in many countries but in many cases this introduces new challenges around data quality, storage and management (Pearce, 2014).

Anthropogenic processes such as deforestation affect groundwater recharge (Brauman et al., 2014; Le Maitre et al., 1999), but the impacts vary depending on climate and the geology of the aquifers. These factors also influence the likelihood that contaminates will be leached from the surface into groundwater. The complexity of the recharge and transport processes may be enhanced or reduced as a function of climate change or land use changes. Variability in climate may also confound trends related to heavy pumping (or reversal of negative trends due to deliberate human interventions), as can human factors and observation errors.

PRINCIPLES OF AN ECOSYSTEM SERVICE AND RESILIENCE APPROACH TO GROUNDWATER-DEPENDENT AGRARIAN SOCIO-ECOLOGIES

GROUNDWATER IMPACTS

The substantial challenges in detecting impacts to groundwater resources and dependent ecosystems, implies the need for knowledge of the systems, precautionary principles to be applied, some kind of vigilance over extended times through monitoring, and implementation of early corrective measures to reverse degrading trends. It is critical to identify priority areas (e.g. important groundwater-dependent wetland systems) and areas of highest vulnerability to degrading trends, in order to be pro-active in monitoring (e.g. early warning) and management. In the face of limited capacity for monitoring, maximum use of traditional knowledge of the dynamics of groundwater systems is a crucial part of better community-based groundwater management (see also Section on Management and Adaptation Strategies).

HUMAN IMPACTS

For the populations dependent on groundwater-based ecosystem services for their livelihoods, evaluating their resilience under trends of degrading ecosystem services requires understanding of their social capital, options for local management, broader engagement in management processes, and their adaptation options and capacity. It is critical to evaluate if they have alternate sources of water to rely on, whether they can augment groundwater resources through strategies such as capturing, infiltrating and storing flood waters, if they have influence on decisions at a higher level regarding resource allocations and remediation efforts, and ultimately if they can develop alternative livelihoods not, or less, dependent on groundwater either in their area or by migrating (Moench and Stapleton, 2007). All of these capabilities hinges on knowledge, social capital, coherence and empowerment, which may be outside the groundwater sector but are never-the-less decisive in future sustainability of these groundwater-dependent socio-ecologies or their transition into new social structures. Recognizing the heterogeneity of these population groups is critical. Gender and other social dimensions need to be clearly spelled out to fully understand vulnerability and enhance resilience.

WHAT DOES IT MEAN TO ADOPT AN ECOSYSTEM SERVICES AND RESILIENCE-BASED APPROACH TO MANAGEMENT OF GROUNDWATER?

- Protection of critical recharge areas so that quantity and quality of water reaching aquifers and important groundwater-dependent ecosystems is not degraded and their services not undermined
- Identification and participatory valuing of the ecosystem services from groundwater-dependent ecosystems – who benefits and how much – so that trade-offs can be properly quantified
- Regulation of the use of groundwater so that some direct benefits can be achieved but without degrading basic ecosystem functions and the (indirect) benefits derived from groundwater-dependent ecosystems
- Increasing participatory monitoring and trend assessment – not just of groundwater but also the groundwater-dependent ecosystems – to improve understanding of linkages and ecosystem functioning and enable adaptive management
- Raising awareness of (and increasing capacity of assessing) the links between groundwater and surface water and hence the role groundwater plays in maintaining many key ecosystems
- Advocacy at political levels for a balanced protection/development of groundwater resources using the Ecosystem Services and Resilience-based
- Allowing certain level of (controlled, temporary) groundwater overdraft in order to make room for farmers to generate income and transition into other non-groundwater-dependent livelihoods

The application of an ecosystem services and resilience-based approach to management of groundwater is briefly illustrated in the following two examples. Much more inter-disciplinary work along these lines is needed.

CASE 1: GAMAMPA: A GROUNDWATER-DEPENDENT WETLAND IN SOUTH AFRICA

The GaMampa wetland was widely believed to make a significant contribution to dry season river flow in the Mohlapitsi River, South Africa. The Mohlapitsi River is an important tributary of the Olifants River, which is one of the principal rivers flowing through, and hence maintaining the ecology of, the Kruger National Park. The park receives more than one million visitors a year, so the river is very important both environmentally and to the national economy.

Flow analyses indicate that despite comprising just 0.6% of the catchment area, the Mohlapitsi River contributes on average 16% of the dry season flow of the Olifants River. Additional studies of the GaMampa wetland revealed that by far the largest flux of water into the wetland is groundwater, coming to the surface in a number of springs. It is this groundwater that supports both the wetland and the dry season river flow. The wetland acts primarily as a conduit for groundwater flows originating in the upper catchment rather than a significant source of water in its own right.

The wetland provides a range of ecosystem services for communities living close to it, including provision of edible plants, building materials, fuel wood, cultivation and livestock grazing. These make an appreciable contribution to food security, household income and welfare. Studies show that the total annual net financial value of wetland benefits is $ 83,623. Benefits derived from the wetland vary a lot across households. The net financial value ranges from $17 to $2,625 per year, with an average of $211 per household. For many households the cash income generated from the wetland is approximately half of the average monthly cash income from all income sources. Crop production contributes the highest gross and net financial value, whereas sedge collection (for handicrafts) yields the highest cash income.

Thus the groundwater originating in the Mohlapitsi catchment is important locally within the GaMampa wetland but also, because of the hydrological interconnection, the water resources of the region and the ecology of a globally important national park. Careful management of both the upper Mohlapitsi catchment (the recharge zone) and the wetland (the discharge zone) are important to ensure long-term sustainability and an equitable distribution of the benefits that the groundwater provides.

Source: McCartney et al., 2011

CASE 2: EXCLOSURES IN THE NORTHERN HIGHLANDS OF ETHIOPIA

The establishment of exclosures (i.e. areas closed for grazing and agriculture) is a common practice to reverse land degradation through vegetation regeneration in the semiarid highland areas of northern Ethiopia (Descheemaekeret al., 2009). Most exclosures are established on steep, degraded hillslopes in community rangeland. Exclosures are effective in restoring vegetation and increasing ecosystem carbon stock and aboveground biomass and biodiversity, in restoring degraded soils, and controlling runoff, sediment and sediment-associated nutrient losses. As a consequence, infiltration is enhanced. Part of the infiltrated water, which is not transpired percolates down and contributes to interflow or groundwater recharge, resulting in new springs, which are used for irrigated agriculture and domestic water uses. Exclosures are also effective in providing multiple economic benefits for local communities through increased livestock feed, bee keeping (i.e., honey production), and non-timber forest products. There is substantial scope for mobilizing local communities' support for establishing exclosures, given that the majority has a positive view on exclosure effectiveness in restoring degraded ecosystems and to improve ecosystem services. However, long-term assessments are needed to ensure sustained improved water capture and recharge as increased biomass (and in particular trees and shrubs) may increase evapotranspiration and reduce recharge with impact on downstream areas. Also, some concerns have been raised related to the negative impacts of exclosures on the availability of fuel wood and the limited short-term impacts in improving smallholder livelihoods. Addressing local concerns and attaining broader policy support are critical for the uptake, out-scaling, and sustainability of exclosures.

Source: Wolde Bori, IWMI

TYPOLOGY OF GROUNDWATER-DEPENDENT AGRARIAN SOCIO-ECOLOGIES

Groundwater-dependent agrarian socio-ecologies, or here shortly GDASEs, can be organized into a typology based on the range of direct and indirect groundwater-related ecosystem services they rely on. In other words, the precise combination of direct and indirect services defines the nature of the groundwater economies across different parts of the globe. Some examples (Shah et al., 2007) are:

1. Arid agrarian systems
2. Industrial agriculture systems
3. Small-holder intensive farming systems
4. Extensive pastoralism

In Africa, many smallholder farmers rely on farming groundwater-dependent wetland or flood plain areas in a seasonal pattern, examples are the *fadama* systems in Nigeria (Nkonya et al., 2010), and the *dambos* in Zambia and Malawi (McCartney et al., 2010). Hence, in defining a broad 'typology' of situations that combines conditions under which groundwater occurs, the extent to which it is developed for society, associated consequences in the provision of services from groundwater-dependent ecosystems, and the trade-offs between direct and indirect groundwater services, becomes important. Further, the typology must include or lead to strategies for managing groundwater resources, and it must consider various factors that influence groundwater accumulation, movement and quality and the stresses to which aquifers are exposed, both natural and anthropogenic.

The focus of developing a typology for GDASEs involves consideration of key determinants defining the relationship between groundwater resources and the ecosystem services that these provide (Figure 2). A pertinent typology also represents variability and trends with respect to various dynamic factors that are internal to the resource - recharge, discharge, quality, etc. - and internal to the societies dependent on the resource - energy, livelihoods, markets, etc. Overarching factors such as climate affects both elements in such a typology.

Developing a typology of GDASEs has three clear purposes. Firstly, it is important to set the right objectives when combining traditional approaches in developing and managing groundwater in conjunction with protecting ecosystems dependent on aquifers and the ecosystem services that they provide. Secondly, the typology must lead to building 'scenarios' or trajectories that describe the role, status and projections regarding aquifers as part of the larger socio-ecological system, including an understanding of the precise nature of trade-offs between the extractive aspects of groundwater development of aquifers and the indirect ecosystem services provided by these aquifers. While doing so, understanding the hydrogeology of aquifer systems – type of aquifers (unconfined / confined / perched / leaky) and aquifer settings (alluvial, consolidated sedimentary, volcanic, crystalline, carbonate,

FIGURE 2. Principal determinants of the typology of groundwater-dependent agrarian socio-ecologies (GDASEs)

mountain) – is as important as the nature of services they provide, e.g. mountain systems are more likely to provide drinking water services through natural discharge to springs, whereas alluvial systems might provide a similar service of drinking water, but through wells to large sections of the society. Thirdly, discussing the opportunities in different scenarios can help shape integrated strategies and interventions at different scales in forging programmes and policies on water, land and ecosystems, many of which continue to exist in silos across large regions of the world.

The dynamics of GDASEs typically follow certain trajectories. In South Asia, a generalised four or five-stage progression has been described (Shah, 2009, COMMAN, 2005). Enabling improved 'future' scenarios is a consequence of understanding current situations and developing future strategies through an analysis of interventions that try to balance between the 'extractive' potential (direct services) of groundwater for social and economic development and its 'ecosystem' role (indirect services) in ensuring sustainability of the larger natural resource base. It is however, important to remember that while doing so, trade-offs between direct and indirect services are inevitable.

Figure 3 illustrates the 'domains' created through the four combinations of high and low groundwater dependence for direct human use and high and low dependence for indirect services. One of the key research questions here would be to understand the relationship between these domains and to test out the extent of 'elasticity' between domains, i.e. whether transitions from one domain to the other are linear or cyclic (as depicted in Figure 3i). The same framework can be used to identify regions that fall into specific categories. This is shown with a broad illustration using certain aquifer systems in India (Figure 3ii) (Kulkani et al., 2015). Similarly, this framework can also be used to categorize different GDASEs at a global level (Figure 3iii), although these could be further nuanced through a more detailed understanding of each of these classes. Finally, strategy development, based on a scenario building effort, can support detailed groundwater management and governance agendas for the four domains. The indicative terminology representing unique strategies for managing groundwater resources in each domain are given in the WLE Ecosystem Services and Resilience Framework (WLE, 2014). Research embedded within such a framework will be able to capture the typology of GDASEs with regard to the two broad roles that groundwater plays in the wide-ranging socio-ecologies across the world today.

MANAGEMENT AND ADAPTATION STRATEGIES

The contribution of groundwater to human development, in particular to drinking and agricultural water security, has been phenomenal. Although its use has been prevalent for millennia, it wasn't until recently that the need to 'manage' groundwater and 'adapt' to its depletion and scarcity became important. Groundwater management is, therefore, an evolving discipline. Regions and countries around the world are struggling to sustainably manage groundwater in the wake of rapid improvements in drilling and pumping technologies that have allowed for a manifold increase in abstraction over the past fifty years.

Growth in groundwater use has peaked in USA, Mexico, Spain and North Africa and is beginning to plateau in South Asia. The latter is due to increasing costs and trade-offs associated primarily with groundwater-irrigated agriculture as well as contradictory and poor regulation and lack of enforcement. In Sub-Saharan Africa, Southeast Asia and Latin America, groundwater use is just beginning to grow (Shah, 2014). However, there do

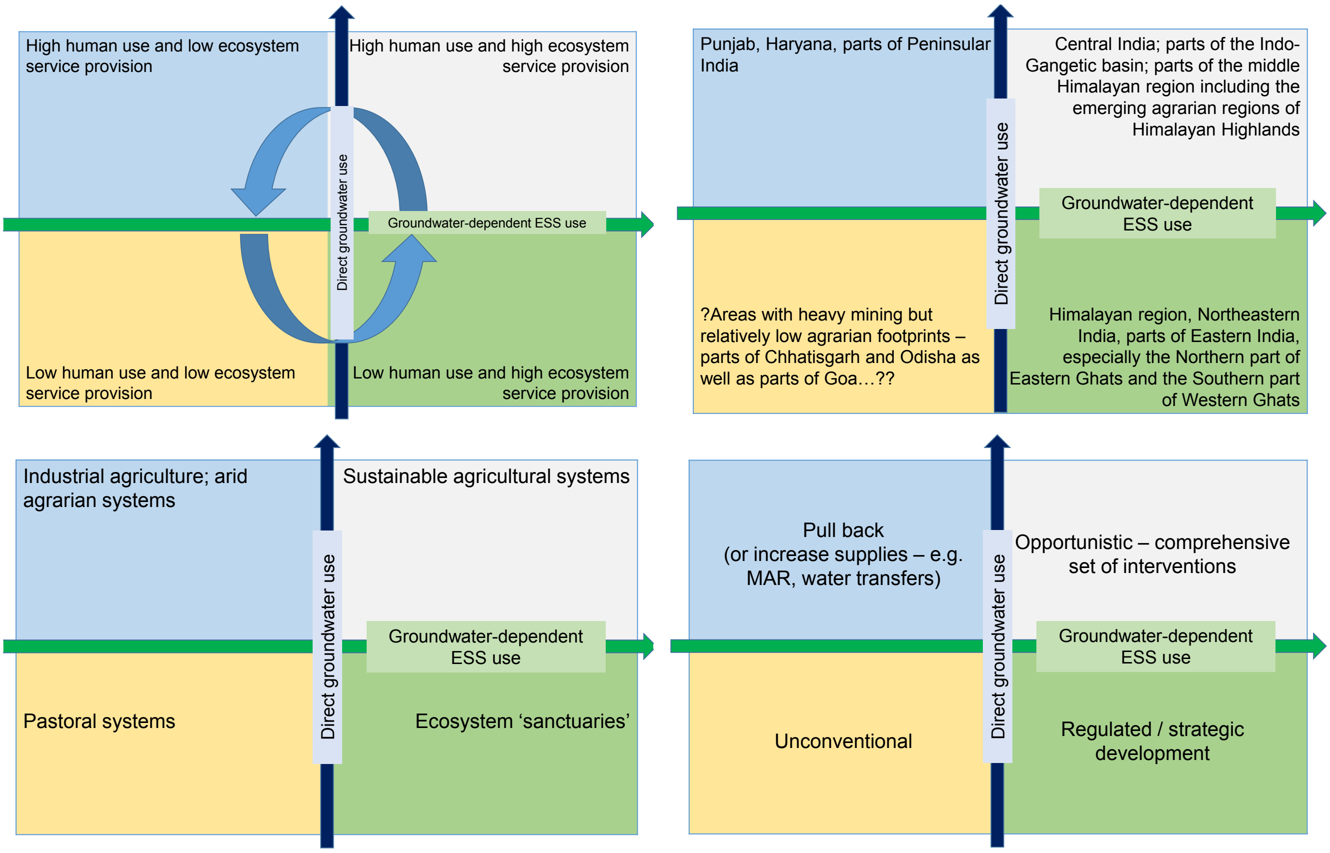

FIGURE 3. A framework to define a typology of GDASEs. (i) Domains of interrelationship between direct groundwater use (y-axis) and groundwater-dependent ecosystem service (ESS) use (x-axis) (ii) Indicative examples of how ecologies in different regions in India are characterised using the framework, with a broad-sweep (iii) and at global level (iv) Strategic interventions to suit the four types

not seem to be any clear answers to how best to ensure long-term sustainability of groundwater. Each region faces a unique set of hydrogeological and socio-ecological conditions (Figure 4), which determine its pathway towards groundwater management. Thus, while it can be immensely useful to learn from the experience of other regions and countries, caution is required in transferring management strategies from one set of circumstances to another (Shah, 2014).

We can broadly classify groundwater management and adaptation strategies into six overlapping categories (Figure 5). The first three categories refer to the instruments of governance – government-led regulation, community-led self-governance, and market-led instruments; the latter three refer to the approaches to governance – supply augmentation, demand reduction, and indirect approaches. In the following, each strategy is briefly explained. Table 1 provides examples and references for each.

1. **Command and Control:** These approaches comprise of groundwater laws, regulations and entitlements as well as rules to check the extent of groundwater abstraction. These may also include regulations that apply only beyond a certain threshold of groundwater abstraction. The Central Groundwater Board in India, for instance, estimates level of groundwater development (annual extraction as a proportion of annual renewable recharge) to classify community development blocks into *'safe', 'semi-critical, 'critical,* and *'over-exploited'* zones. A similar groundwater regulation regime is followed in Iran by classifying the country into *'Free', 'Restricted'* and *'Critical'* areas (Hekmat, 2002). Other examples include a plethora of water and groundwater laws and entitlements, as in Oman (FAO, 2009; van der Gun, 2007), Jordan (Venot and Molle, 2008), Syria, Iran, Israel, Saudi Arabia, Yemen, India (Phansalkar and Kher, 2006; Planning Commission, 2007), China (Wang et al., 2009), Spain (Hernandez-Mora et al., 2003; Lopez-Gunn, 2003), Kansas (Shah, 2014), Australia and New Zealand.

Groundwater laws are easy to make but almost impossible to enforce. Enforcement requires financial as well as institutional resources, which are often missing in developing countries. Even in countries like USA, with (relatively) small number of large users and significant enforcement capacity and resources, the effectiveness of

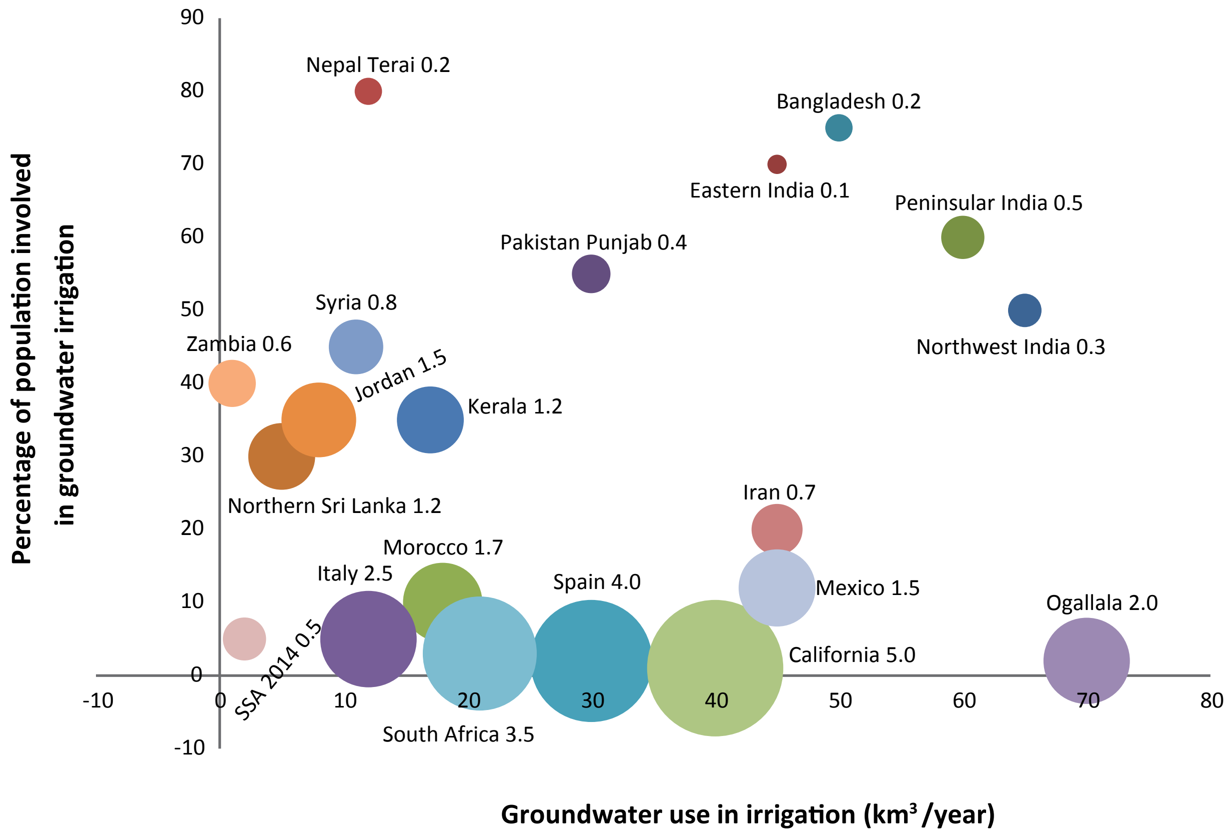

FIGURE 4. Prominent groundwater-irrigation economies. Figures in circles indicate the value of productivity of groundwater in irrigation (US$/$m^3$) (*Source*: Shah, 2014)

"Command and Control" instruments is debatable. Shah (2014) concludes that *"despite intensive governance, sustainable groundwater is still a work in progress in many parts of the USA"*. The only instances where these instruments seem to have worked to some extent are arid, autocratic states like Oman and Saudi Arabia where groundwater regulation is a matter of life-and-death.

2. **Community Management:** Groundwater is a classic Common Property Resource (CPR) and therefore susceptible to the 'tragedy of the commons' (Ostrom et al., 1999). Community management approaches refer to instances where user-communities have been entrusted with, or self-adopt, the responsibility of sustainable groundwater management. In Spain, basin-level groundwater federations plan and manage groundwater. Likewise, in Mexico, aquifer management councils (COTAS) were

FIGURE 5. Groundwater management and adaptation strategies

created to generate information, educate farmers and manage groundwater overdraft. In India too, the FAO-supported Andhra Pradesh Farmer Managed Groundwater Systems (APFMGS) experimented with community management. However, studies suggest that while these community organizations have done well in gathering information and educating farmers, their effectiveness in checking groundwater overdraft is questionable (Hernandez-Mora et al., 2003; Lopez-Gunn, 2003; Shah, 2003; Sandoval, 2004; Shah, 2009; Verma et al., 2012; Shah, 2014). Implementing effective community management is effort and time-intensive; requires enlightened users and strong leadership; and successful cases tend to be few, localized and far between.

3. **Market Instruments:** Volumetric pricing of groundwater is considered an effective instrument or incentive for promoting efficient groundwater use, especially in developed countries (Refsgaard and Vangsgaard, 2011). However for more universal uptake, this would require effective metering of groundwater use, which becomes difficult when users are small, numerous and geographically dispersed. Moreover, pricing groundwater at its actual social value is politically infeasible in most countries where groundwater use is critical to sustaining millions of rural livelihoods or when groundwater is used for basic needs such as drinking water. When it is difficult to price groundwater, energy prices for lifting can be a surrogate for groundwater pricing. Since energy is required to pump groundwater beyond rudimentary use, its pricing can dictate groundwater use. However, in countries like India, China, Mexico and Iran, energy is highly subsidized and these subsidies often become the prime drivers of groundwater overdraft. In cases where groundwater use is highly productive, such as in the Mediterranean region – Italy, Spain, Turkey, Cyprus, Jordan – even effectively priced energy is unlikely to check groundwater overdraft. When the value created by using groundwater is as high as US$ 5/ m^3, demand for groundwater is too inelastic to respond to small changes in prices (Garrido et al., 2006). So, pricing of groundwater (or of the surrogate, energy) is likely to work only when measurement of use is easy and when demand is highly price-elastic. Such is the case in the High Plains aquifer of USA where Pfeiffer and Lin (2013) estimated that a 2.6 percent increase in the price of natural gas would lead to a reduction of groundwater use by more than 60 percent.
    The ecosystem services framework also creates opportunities for alternate types of market instruments: Payment for Ecosystem Services (PES) or Payment for Watershed Services (PWS). In these, upstream actors are compensated by downstream water users for undertaking activities that enhance a water resource (Bennett et al., 2013). Water resource management strategies of this kind range from strict market arrangements to taxpayer-funded investments and can even include tradable credits (Goldman-Benner, et al., 2012). To date, the vast majority of these schemes have focused on surface water resources, primarily on water quality and on water yield (Brauman, 2015). In a groundwater-focused scheme, downstream groundwater users compensate upstream residents for either increasing groundwater recharge through activities that increase infiltration, decreasing aquifer depletion by reducing pumping, or by curtailing polluting activities (Tuinstra and Wensem, 2014; Peñuela-Arévalo and Carrillo-Rivera, 2012; Klöve et al., 2011). A recent study by Brauman et al. (2014) demonstrated the impact and economic value of different land cover transitions on groundwater resources. Most ecosystem services based payment programs compensate upstream actors based on their activities, not on measured differences in water resource outcomes. While this overcomes many of the problems of monitoring and enforcement identified above, it also makes it difficult to ascertain whether water resources are actually being improved (Peñuela-Arévalo and Carrillo-Rivera, 2012). Designing programs appropriate to the specific hydrogeologic setting should help ensure desired impacts (Ponette-González et al., 2014). Concerns have been raised about the equity (Leimona et al., 2015) and sustainability (Klöve et al., 2011) implications of relying on a market-based mechanism to enhance water resources.

4. **Demand Management:** Restricting the demand for groundwater abstraction is perhaps the most challenging of management strategies. Given the salience of groundwater to the lives and livelihoods of users, groundwater managers struggle to convince users to reduce demand even when failure to do so may put future use in jeopardy. Perhaps the most commonly discussed strategy for groundwater demand management in agriculture is the adoption of "water-saving technologies", such as drips and sprinklers. These technologies offer improved application efficiency by cutting down evaporation and seepage losses. However, all evidence from the field suggests that the adoption of these technologies may lead to some reduction in overall groundwater abstraction (and return flows) but not in terms of evapotranspiration/ depletion, therefore leaving the de-stocking of the aquifer largely unchanged (Verma et al., 2004; Shah et al., 2005; Pfeffer and Lin, 2013; Gollehon and Winston, 2013). Moench et al. (2003) talk about a completely "different approach to groundwater" when they discuss the merits of 'adaptation' as opposed to mitigation. They argue that communities adapt to changes in groundwater availability by

shifting to less water-intensive crops or shifting to less groundwater-intensive occupations. Prerequisites for effective groundwater demand management seem to be a heightened sense of crisis, small and homogenous user groups and enlightened leadership.

5. **Supply Augmentation:** Developing alternative water sources, including through inter-basin transfers, desalination, recycling and reuse and managed aquifer recharge (MAR), are the key components of the supply augmentation approach. In western USA, crowding out groundwater wells by importing surface water was a key strategy in Arizona. Spain's proposed water transfer project from Erbo river; India's grand 'National River Linking Project' proposal; Gujarat's inter-basin transfer through the 400 km long recharge canal – *Sujalam Sufalam*; and China's South-to-North water transfers are all examples of supply augmentation, to partly off-set groundwater depletion, through massive water transfers. Tarun Bharat Sangh's Magsaysay award winning work in Alwar (Shah, 2009) and Saurashtra's decentralized water harvesting and groundwater recharge movement (Sakthivadivel, 2007; Shah, 2009; Verma and Palrecha, 2011) are examples of supply augmentation through community action. Conjunctive management of surface and groundwater, through ideas such as the 'Ganges Water Machine'[1] is another avenue for supply augmentation (Revelle and Lakshiminarayana, 1975; Foster and van Steenbergen, 2011; Evans et al., 2012; Smakhtin, 2013). Concern is that these solutions may simply export the impacts on ecosystem services elsewhere (Zhao et al., 2014).

6. **Indirect Approaches:** Indirect approaches refer to management strategies that lie outside the water sector but can have significant impact on groundwater draft. We already discussed above how energy prices can be a good surrogate for groundwater pricing (see Shah et al., 2004a; Shah and Verma, 2008; Mukherji et al., 2010). Similarly, a region or country's food policies are intricately linked with its groundwater sustainability. In 1992, Saudi Arabia spent US$ 2 billion to subsidize domestic wheat production when they could have procured the wheat from the international market at less than 20 per cent of that (Postel, 1992). When Saudi Arabia decided to give up on wheat self-sufficiency and started importing wheat to supplement domestic production, groundwater use in agriculture declined (Abderrahman, 2001). Soltani and Saboohi (2008) recommend a similar shift in policy for Iran. The basic justification for India's grand 'National River Linking Project' is the need to expand irrigated areas to maintain food grain self-sufficiency. Studies in India (Verma et al., 2009; Verma, 2010) find that paradoxically as a result of India's energy and food policies, water-scarce north-western India ends up exporting *virtual water*[2] to water-abundant eastern India. Recent interest in promoting solar-powered irrigation presents another opportunity to influence groundwater abstraction through energy policies (see Shah and Kishore, 2012; Shah and Verma, 2014; Shah et al., 2014). Thus, groundwater management strategies are intricately and inevitably linked to food, agriculture and energy policies. The need is for policy makers to recognize these inter-linkages.

[1] The Ganges Water Machine idea argues, in part, for pre-monsoon depletion of groundwater aquifers to maximise capture of monsoon rainfall as underground storage.
[2] Virtual water is the water embedded in the production process and final product of any commodity.

TABLE 1: GROUNDWATER MANAGEMENT AND ADAPTATION STRATEGIES: EXAMPLES AND CONDITIONS

APPROACH	INSTRUMENTS / APPROACH	EXAMPLES	ENABLING CONDITIONS	CONSTRAINTS TO EFFECTIVENESS
1. Command and Control	Water laws; entitlements; licensing; sectoral priorities; rules on well depth, spacing and safe yield; rules based on extent of resource development	United States (Shah 2014); Australia; North China (Wang large et. al., 2009), India (Phansalkar and Kher, 2006); Spain (Hernandez-Mora et al., 2003; Lopez-Gunn, 2003); Oman FAO 2009; van der Gun, 2007), Jordan (Venot and Molle 2008)	Strong state; small number of users; ability to monitor and enforce	Large number of small users; lack of popular support and political will; limited enforcement capacity
2. Community Management	Tradable property rights; formal and informal rules implemented by communities; participatory groundwater management; crop water budgeting	Mexico (Sandoval, 2004; Shah, 2003; Shah et al., 2004b); India (COMMAN, 2005; Planning Commission, 2007; Shah 2000; 2011; Verma et al. 2012); Spain (Hernandez-Mora et al., 2003; Lopez-Gunn, 2003); Philippines; Sri Lanka	Years of experience with GW; Severity of crisis; Strong leadership; Small, relatively-homogenous groups; communication (traditional) networks	Lack of formal authority and enforcement mechanisms; high dependence on individual leadership
3. Market Instruments	Volumetric pricing; tradable property rights; scarcity pricing; pricing of energy to abstract GW; tariffs and subsidies	European Union; USA; Urban China; Mexico (Sandoval, 2004; Shah, 2009; Scott, 2013); Iran; Saudi Arabia; India; Thailand	Small number of large users; easy to monitor GW extraction; deep-rooted culture of metering; high price elasticity of GW demand	Small, numerous and dispersed abstractions; costly metering; highly subsidized energy for pumping; high productivity of GW leading to price-inelastic demand
	Incentives for conservation (incl. PES and PWS)	USA, China, Latin America (Brauman, 2015; Bennett et al., 2013)	Value of improvement to water resource higher than cost of improving water resource	Need to demonstrate clear benefit on short timeline. Weak property rights.
4. Supply Augmentation	Managed Aquifer Recharge; adding storages; physical water transfers; catchment management; managed conjunctive use; desalination; recycling and reuse	Middle East – Israel; Morocco (Shah, 2014); Cambodia; Saurashtra (Sakthivadivel, 2007; Shah, 2009; Verma and Palrecha, 2011); Ganges water machine (Revelle and Lakshiminarayana, 1975; Foster and van Steenbergen, 2011)	Immediate response to recharge; post project resources for maintenance; cheap energy / paying capacity; severity of crisis	Lack of strong local leadership; distrust among wider aquifer community
5. Demand Management	Cropping patterns; optimizing water productivity through ICT; water saving technologies; alternative livelihoods (post-depletion sustainability)	South Asia and North China (Moench et al., 2003); India (Shah, 2009; Singh, 2009); China (Aarnoudse et al. 2012)	Know-how; enlightened leadership; heightened crisis; action in small, homogenous groups	High variability in access and dependence; possibility of externally supported supply augmentation
6. Indirect Approaches	Energy policy; food policy	India (Shah et. al., 2004; Shah and Verma, 2008; Verma et. al., 2009; Shah and Verma, 2014; Shah et al., 2014)	Recognition of inter-linkages; Inter-sectoral and cross-sectoral interactions; strong political will	Silo-approach to resource management; lack of political will

ASSESSMENT TOOLS TO SUPPORT AN ECOSYSTEM SERVICE AND RESILIENCE APPROACH TO GROUNDWATER

Tools" in the present context are generally methods and approaches that help guide researchers, practitioners or policymakers to think and apply information in a structured way to create knowledge and make decisions. However, if a tool is too simple or prescriptive then there is a danger that it replaces, or over-rules, critical, analytical thinking and discussion. The aim of most tools and approaches should not be to create globally standardised solutions but to ensure that the specialist biases are tamed, that solid evidence is gathered and used and that the voices of society's most vulnerable are heard and given weight. While decisions are critically dependent on the political context and power relations, evidence-based research and tools serve to counteract biased decisions and empower stakeholders.

A good tool should bring stakeholders together so that complex problems are examined from different perspectives. Such processes can be messy and time-consuming, but a good tool provides structure so that such discussions and decision-making are informed by evidence and a shared understanding of needs and goals.

Annex 1 presents a selection of freely available guidelines and tools (and their URLs) that may have useful application in looking at groundwater and ecosystems services. It is adapted, expanded and updated from "Guidelines and Tools for Rural Water Supply" (Smith and Furey, 2012).

No tools or guidelines were found that specifically focus on the ecosystems services of groundwater, however. Most aspects are captured by a range of tools and resources developed for IWRM[3] or WASH[4].

WEBSITES AND ONLINE TOOLS

Perhaps the two most comprehensive online portals are currently **Akvopedia** and the **Sustainable Sanitation and Water Management** (SSWM) website. They are structured differently, but provide useful information in themselves and act as portals to specialist information. Akvopedia has a compilation of decision and assessment tools, but with an emphasis on WASH. The Natural Capital Project's Integrated **Valuation of Ecosystem Services and Trade-offs (InVEST)** tool does not currently have a groundwater-specific module, but one is planned. More importantly, as an integrated tool it may be a useful resource for those planning to do an ecosystem services assessment.

The **Participatory Groundwater Management toolkit** has been developed by Meta Meta Research and includes useful training materials that can be adapted to different contexts.

The Global Water Partnership (GWP) provides an online **IWRM Toolbox** that guides users through Integrated Water Resource Management in three sections: (1) The Enabling Environment; (2) Institutional Roles; and (3) Management Instruments. The guidance is supported by case-studies from around the world.

WWF provides an online tool called the **Water Risk Filter**, which allows commercial organisations to assess their exposure to water risks. The questionnaire covers physical, regulatory and reputation risks and groundwater is included very rudimentarily as one of the resources to be assessed.

The **ARIES ecosystem services model** includes groundwater among its modules: Though they focus on surface water, readers might also find it useful to know about Vigerstol and Aukema's (2011) comparison of models designed specifically to model hydrology (they focus on the Soil Water Assessment Tool – SWAT) and models that are designed for ecosystem services assessment.

DATA AND INFORMATION

Like models, tools are only as good as the data and information put into them. The availability of groundwater data is highly variable and in some regions of the world it is very limited in geographic and temporal extent and the quality control should always be interrogated and not taken at face value. IGRAC is the mandated UN organisation for groundwater data at a global scale but other resources also exist online for rapid assessments:

- Africa Groundwater Atlas and Literature Archive
- WHYMAP: World-wide Hydrogeological Mapping and Assessment Programme
- Hydrogeologists Without Borders (UK): Borehole Log Database

WaterAid has developed a series of frameworks that guide the design and implementation of their country programmes so that they are focused on sustainability and reaching the poorest and most marginalised communities:

- Water security framework
- Sustainability framework
- Equity and inclusion framework

A multitude of tools exist that could be applied to issues around groundwater and ecosystems services. For best results, practitioners and researchers need a clear understanding of when and what tools to apply, including:

- The nature of the problem or question to be tackled, and the desired outcome.
- The context in which this problem is occurring.
- The quantity and quality of data and qualitative information available.
- The capacities of user and the relevant stakeholders to use and engage with the tool.
- If the available tool does not fit all of the above, then how can it be adapted and improved.

[3] IWRM: Integrated Water Resources Management
[4] WASH: Water, Sanitation and Health

Photos: Karen Villholth/IWMI

RESEARCHABLE TASKS

1. Develop better tools to understand hydrological and environmental inter-linkages between groundwater, surface water and ecosystems, especially over extended spatial and temporal scales and across watersheds;
2. Develop and refine economic as well as non-monetary valuation methods for ecosystem services linked to groundwater;
3. Asses approaches to payment for ecosystem services provided by groundwater systems. Under this, also identify best monitoring strategies for assessing impact of implementation of payment for ecosystem services provided by groundwater;
4. Synthesize world-wide experience with local management of groundwater and associated ecosystems. What are the roles of the farmers, local and higher level governance, private enterprise, NGO's, and research entities?
5. Develop methods for determining environmental water requirements for groundwater-dependent ecosystem services. Looking at the transferability of models to systems with less data but similar physical layouts;
6. Document and synthesize multiple case studies and groundwater policy experiences from different parts of the world to serve as learning examples of what has worked (or not) at different scales;
7. Assess the impacts on groundwater-dependent socio-ecologies of decisions outside the groundwater sector;
8. Assess and understand the role of politics in groundwater socio-ecologies in order to improve access and allocation as well as regulation and enforcement;
9. Assess cultural/poverty aspects of ecosystem services in the context of groundwater development and use for irrigation and how it varies in different continents;
10. Investigate early options for ensuring access to groundwater irrigation and long-term benefits for the poorest farmers in sub-Saharan Africa
11. Explore the ecosystem benefits of conjunctive groundwater-surface water use in irrigation for increasing resilience to climate change
12. Explore the ecosystem benefits of shifting India's rice-wheat system eastward

KEY MESSAGES

- In recent decades, groundwater development has played a crucial and increasing role in sustaining agrarian livelihoods in the developing world;
- However, with increasing groundwater development, ecosystem services on which the agrarian socio-ecologies depend have been degraded;
- Aquifers as ecosystems need to be viewed in an inclusive manner with agriculture being one of the 'stakeholders', others being wetlands, fisheries, drinking water, dry season river flows, and so on;
- Groundwater-related decisions are usually made based on economics and livelihoods considerations from groundwater pumping. However, the beneficiaries of groundwater and their ecosystem services are much broader;
- Groundwater underpins (or gets implicated in) most ecosystem services for environment and society; degrading aquifers magnifies the decline of a range of ecosystem services;
- Groundwater supports ecosystem services, but is also critically dependent on the health of the catchment ecosystems;
- Groundwater management needs to recognize the spatially dispersed but interlinked nature of ecosystem services derived from or impacting aquifers;
- Managing groundwater-dependent ecosystems services is possible through regulating activities that influence them, e.g. land use, waste handling, agro-chemical use, groundwater abstraction, water harvesting, etc.
- Understanding the political dimension of groundwater-dependent socio-ecologies is essential in order to assess how ecosystem services are allocated and who benefits from them - so that livelihoods for small farmers and the poor can be improved;
- Win-win opportunities to maximize benefits from groundwater and linked ecosystem services sometimes exist and should be the first priority of research and management. However, in most cases, trade-offs between various ecosystem services come into play;
- A change in mind-set is needed. Rather than managing ecosystem services *per se*, we need to manage the socio-ecologies dependent on groundwater ecosystem services;
- For this to happen, inter-disciplinary and inter-sectoral dialogues are critical; without these, socio-ecological resilience is unachievable;
- Similarly, surface-groundwater and irrigation-drinking water divides must be bridged through inter-disciplinary research and policy debate;

(Continued)

KEY MESSAGES (CONTINUED)

- Research, stakeholder engagement, and policy making must proceed hand-in-hand in a participatory format; policy arguments should not emerge as appendage or after-thought to research and engagement;
- Relevant management must take into account the groundwater-ecosystems typology (e.g. hydrogeology, response times, level of development, macro-economic and macro-political framework, legal-institutional framework and socio-cultural capital) in order to devise efficient solutions;
- Politicians are unlikely to act on recommendations that jeopardize their political capital; yet they act on ideas that promise political dividend;
- Much that influences aquifers and its ecosystem services through human interaction results from decisions/interventions outside the groundwater sector. Hence, it is critical to bring inter-sectoral linkages into research focus;
- Researchers need to articulate their knowledge and recommendations regarding groundwater and socio-ecologies to stakeholders and decision makers in simple-to-understand language.

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ANNEX 1: TOOLS FOR SUPPORTING WORK ON GROUNDWATER AND ECOSYSTEM SERVICES

TOOL NAME	ORGANISATION	WEB LINK	GROUNDWATER	ECOSYSTEM SERVICES	IWRM GENERAL	WASH GENERAL
Africa Groundwater Atlas and Literature Archive	NERC and British Geological Survey (BGS)	http://www.bgs.ac.uk/africagroundwateratlas	✓			
Akvodpedia - Links to Tools	Akvo	http://akvopedia.org/wiki/Decision_%26_Assessment_Tools	✓			✓
Akvopedia	Akvo	http://akvopedia.org/	✓			✓
AQUADUCT - Water Risk Mapping Tool	World Resources Institute	http://www.wri.org/our-work/project/aqueduct/aqueduct-atlas			✓	
Artificial Intelligence for Ecosystem Services (ARIES)	ARIES Consortium	http://www.ariesonline.org/modules/water.html	✓	✓		
Borehole Log Database Borders (UK)	Hydrogeologists Without	www.hydrogeologistswithoutborders.org.uk/index.php/resources	✓			
Equity and Inclusion Framework	WaterAid	http://www.wateraid.org/what-we-do/our-approach/research-and-publications/view-publication?id=d98d98ad-b605-4894-97cf-0c7682e62b04				✓
Geogenic Contamination Handbook	Eawag	http://www.eawag.ch/forschung/ess/gruppen/ehpsy/Behavioural_march_2013.pdf	✓			
Global Groundwater Information System (GGIS)	International Groundwater Resources Assessment Centre (IGRAC)	http://www.un-igrac.org/publications/104	✓			
Guidelines for Drinking-water Quality – Fourth Edition (2011)	World Health Organisation	http://www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en/				✓
GW-MATE Publications	World Bank	http://water.worldbank.org/gwmatepubs	✓	✓		
IWRM Toolbox	Global Water Partnership	www.gwp.org/en/ToolBox/			✓	
Participatory Groundwater Management toolkit	Meta Meta	http://www.groundwatermanagement.org	✓			
Resource Investment Optimization System	Natural Capital Project	http://www.naturalcapitalproject.org/RIOS.html		✓	✓	
SolutionMUS	Winrock International	www.solutionmus.org			✓	✓
Sustainability Framework	WaterAid	http://www.wateraid.org/what-we-do/our-approach/research-and-publications/view-publication?id=0b45ec09-e7d2-43e1-9423-c00f5ff4e733				✓
Sustainable Sanitation & Water Management (SSWM)	Ceecon	www.sswm.info/	✓		✓	✓
Valuation of Ecosystem Services and Trade-offs (InVEST)	Natural Capital Project	http://www.naturalcapitalproject.org/models/models.html		✓		
Violence, Gender & WASH	SHARE Consortium	violence-wash.lboro.ac.uk				✓
Water Risk Filter	Worldwide Fund for Nature (WWF)	http://waterriskfilter.panda.org			✓	
Water Security	WaterAid	http://www.wateraid.org/what-we-do/our-approach/research-and-publications/view-publication?id=6260c684-ddf0-411c-8415-60873a738304			✓	✓
WHYMAP: World-wide Hydrogeological Mapping and Assessment Programme Framework	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)	www.whymap.org	✓			

Photo: Matthew McCartney

CGIAR Research Program on Water, Land and Ecosystems

The **CGIAR Research Program on Water, Land and Ecosystems (WLE)** combines the resources of 11 CGIAR centers, the Food and Agriculture Organization of the United Nations (FAO) and numerous national, regional and international partners to provide an integrated approach to natural resource management research. WLE promotes a new approach to sustainable intensification in which a healthy functioning ecosystem is seen as a prerequisite to agricultural development, resilience of food systems and human well-being. This program is led by the International Water Management Institute (IWMI), a member of the CGIAR Consortium, and is supported by CGIAR, a global research partnership for a food-secure future.

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