



# Management of aquifer recharge and discharge processes and aquifer storage equilibrium



**Groundwater Governance**  
A Global Framework for Action





# Groundwater Governance - A Global Framework for Action

Groundwater Governance - A Global Framework for Action (2011-2014) is a joint project supported by the Global Environment Facility (GEF) and implemented by the Food and Agriculture Organisation of the United Nations (FAO), jointly with UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrologists (IAH) and the World Bank.

The project is designed to raise awareness of the importance of groundwater resources for many regions of the world, and identify and promote best practices in groundwater governance as a way to achieve the sustainable management of groundwater resources.

The first phase of the project consists of a review of the global situation of groundwater governance and aims to develop of a Global Groundwater Diagnostic that integrates regional and country experiences with prospects for the future. This first phase builds on a series of case studies, thematic papers and five regional consultations.

Twelve thematic papers have thus been prepared to synthesize the current knowledge and experience concerning key economic, policy, institutional, environmental and technical aspects of groundwater management, and address emerging issues and innovative approaches. The 12 thematic papers are listed below and are available on the project website along with a Synthesis Report on Groundwater Governance that compiles the results of the case studies and the thematic papers.

The second phase of the project will develop the main project outcome, a Global Framework for Action consisting of a set of policy and institutional guidelines, recommendations and best practices designed to improve groundwater management at country/local level, and groundwater governance at local, national and transboundary levels.

## Thematic Papers

- No.1 - Trends in groundwater pollution; trends in loss of groundwater quality and related aquifers services
- No.2 - Conjunctive use and management of groundwater and surface water
- No.3 - Urban-rural tensions; opportunities for co-management
- No.4 - Management of recharge / discharge processes and aquifer equilibrium states
- No.5 - Groundwater policy and governance
- No.6 - Legal framework for sustainable groundwater governance
- No.7 - Trends in local groundwater management institutions / user partnerships
- No.8 - Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction
- No.9 - Macro-economic trends that influence demand for groundwater and related aquifer services
- No.10 - Governance of the subsurface and groundwater frontier
- No.11 - Political economy of groundwater governance
- No.12 - Groundwater and climate change adaptation

# **Management of aquifer recharge and discharge processes and aquifer storage equilibrium**

## **GEF-FAO Groundwater Governance Thematic Paper 4:**

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## **Executive Summary**

This GEF FAO Thematic Paper reviews the state of management of groundwater recharge, discharge and storage in relation to physical, institutional and social factors.

In the three countries with the highest rates of groundwater overdraft storage declines are accelerating and expose the widespread failure of current groundwater management strategies that are based on the concept of private ownership of groundwater.

However elsewhere there are numerous proven effective management strategies based on the concept of groundwater being a common pool resource. This thematic paper draws attention to case studies from a range of hydrogeological, climatic and societal settings where innovative management has been conspicuously successful in reversing groundwater storage declines (or increases).

A combination of three elements; demand management, recharge enhancement and alternative supplies can sustain or prolong groundwater resources and maximise the value of their utilisation. Embedded within an integrated natural resources management framework, these elements can also enhance agricultural livelihoods and social cohesion and restore water quality and degraded environments. At each location the balance between these major elements, and the selection of methods depends on the availability and cost of surface water resources (natural, stormwater, recycled water), economics and capabilities for managed aquifer recharge and the economics of improving irrigation efficiency and foregoing production.

It is recognised that in the absence of adequate surface water resources, and low rates of replenishment there may be an intentional policy of mining groundwater for irrigation as a transitional pathway to a less water-dependent economy.

Instruments such as setting entitlements, volumetric allocations and use conditions, assist with demand management and allow trading to maximise the utility of the groundwater resource

In some cases new institutions such as catchment water management boards, water banks and water user associations may assist in implementing and sustaining reforms.

Informing and engaging stakeholders in governance has resulted in more resilient outcomes that take better account of local needs.

Importantly, in many settings local action by motivated communities has run ahead of state and national policies and been highly effective in managing groundwater storage, increasing farm incomes and protecting the environment. Clearly, where there are also supportive government policies, local reform is easier to implement.

The paper concludes with a unifying synthesis of pathways through policy reform, based on integrated water resources assessment, and including evaluation of groundwater stress, community capabilities for collective action and the availability of other water resources.

In summary, there are many good news stories about over-allocated aquifers that have been restored to hydrologic equilibrium by a variety of means, and it is hoped that this document will raise awareness of viable alternatives to currently doomed conventional strategies.

## **1. Introduction**

The purpose of this GEF Project Thematic Paper is to review the state of management of groundwater recharge, discharge and storage in relation to physical, institutional or social factors. This is one of a series of Thematic Papers to diagnose historical and current issues and examine examples and prospects of regaining aquifer integrity and function or mitigating further impacts through improved water governance. The paper is intended to illustrate how global benefits can accrue through fresh and unified approaches to groundwater resource management that will halt or retard aquifer storage and water quality declines and the consequences of the loss of the state of equilibrium.

The scope of this paper is at a macro-view level while using localised case studies to illustrate the effectiveness of various strategies and the circumstances that influence success. The paper starts with a summary of current practice and the consequences. This baseline reveals that business as usual is already having serious repercussions, and new strategies are necessary. Next various problem typologies are diagnosed and hierarchy of potential governance solutions proposed. In some cases there are outstanding current examples of historically intractable problems having been overcome, offering confidence to groundwater managers around the globe facing similar situations. Finally, a hierarchy of implementation strategies for innovative policies is suggested, assimilating outcomes of case studies.

This document was prepared by World Wide Ground Water through a team from the International Association of Hydrogeologists Commission on Managing Aquifer Recharge with the support of CSIRO Water for a Healthy Country Flagship Program.

## **2. The state of groundwater governance in relation to the recharge and discharge processes and aquifer equilibrium states „(Baseline)“**

### **2.1 The status of groundwater storage**

Groundwater storage is shown to be declining in all populated continents and the global depletion rate over 2001-2008 was estimated by Konikow (2011) using a variety of methods, but notably including groundwater level changes, as  $145 \text{ km}^3/\text{yr}$  (equivalent to  $0.40\text{mm}/\text{yr}$  of sea-level rise or 13% of current rate of rise). This is largely the result of increased abstraction through the advent of electric powered pumps and improved drilling techniques making groundwater more accessible in larger volumes and from greater depths. Contemporary climate change causing changes in recharge has had a very much smaller impact on storage (Kundzewicz *et al* 2007).

Konikow estimated the cumulative global groundwater depletion from 1900 to 2008 as  $4500 \text{ km}^3$  (see Figure 1 from Konikow (2011)). An alarming feature of this graph is the continuing acceleration in rate of groundwater depletion. Starting from an almost negligible decline until 1950 the rate of depletion between 1950 and 2000 was doubled in the period 2000 to 2008. The fastest decline has been largely focussed in irrigation areas of semi-arid and arid countries, with northern India and United States sharing responsibility for more than half of the overall global depletion. Other significant declines have been observed in Saudi Arabia, North China Plain, the Nubian aquifer and in the north western Sahara. In most of those areas current groundwater recharge is negligible in comparison with extraction and water resources managers regard groundwater as a non-renewable resource. A further 30% of the total estimated decline is from systems in other countries that were not quantitatively evaluated.

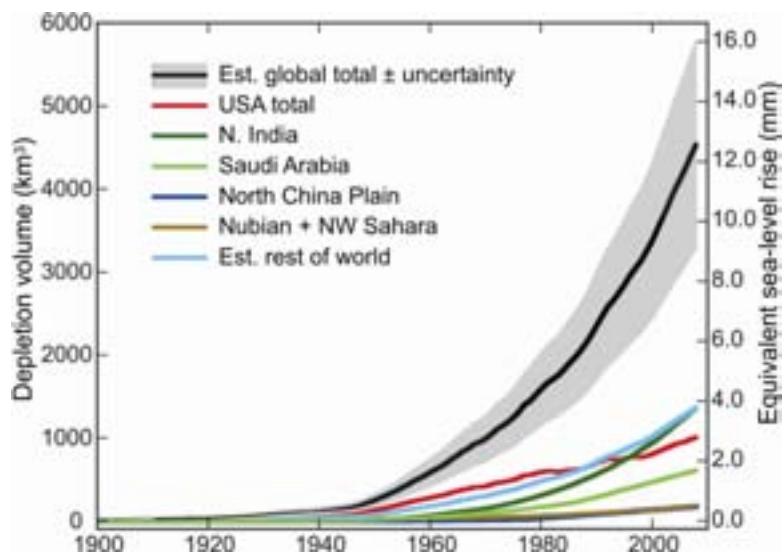


Figure 1. Estimated cumulative global groundwater depletion (1900-2008) (from Konikow, 2011, used with permission).

Comparing these figures with estimates by Margat (2008) of annual exploitation of groundwater of  $800 \text{ km}^3/\text{yr}$  suggests that storage decline is only an aggregated 18% of groundwater extraction. In shallow systems this may be in part be due to induced additional recharge for example as observed in Tamil Nadu, India by Charalambous and Garratt (2009). In general, if return flows to aquifers from irrigation were of the order of 20% of extraction, in systems that are drawn down so that water table no longer influences the recharge volume, then the net decline in natural groundwater discharge would be about  $500 \text{ km}^3/\text{yr}$ . That is the impacts on surface water resources and groundwater dependent ecosystems of groundwater extraction may be much more significant than revealed by the observed change in groundwater storage. While groundwater in places is a relic reservoir resulting from former wetter climates, in many places it is a dynamic flowing system. Global mean natural recharge exceeds  $12,000 \text{ km}^3/\text{yr}$  (Margat 2008) (out of  $106,000 \text{ km}^3/\text{yr}$  precipitation on land; UNESCO and Earthscan 2009) and was on average balanced by natural discharge prior to extraction by man. That is exploitation of only 7% of global natural recharge is sufficient to cause the observed significant storage decline, and related effects on surface water resources and groundwater dependent ecosystems.

Global figures reveal the significance of the storage change issue but the magnitude, causes, consequences and management responses vary enormously among regions. In many places groundwater use is low or sustainable without adverse consequences. The various regions where declines are emergent or significant cover spectra of socio-economic conditions, replenishment and extraction rates. Several typologies will be discussed later.

Consequences of ongoing decline in groundwater storage are (Burke and Moench 2000);

- Deterioration of groundwater dependent ecosystems and depletion of surface water resources
- Higher pumping costs, energy consumption and greenhouse gas release
- Need to deepen wells to maintain supplies, and in general only the wealthiest will be able to pursue the falling water level and we have *the tragedy of the commons*
- Deterioration of groundwater quality, due to upwelling in stratified aquifers or saline intrusion from brackish groundwater or from the sea in coastal aquifers

- Land subsidence where aquifers are confined and aquitards contain clays that are compressible when pore pressures drop (reviewed by Galloway and Burbey 2011)
- Competition for scarce groundwater resources among and between sectors of the economy causing social and political stresses
- Reduced incomes for farmers and industries previously reliant on groundwater
- Migration to cities and closure of services in rural areas as a result of income decline
- Uncertainty in communities concerning their future viability and loss of cohesion.

On the other hand, consequences of not exploiting non-renewable groundwater resources include denial of the opportunity to current generations of opportunities for development, increased income, improved health, and establishment of more stable human settlements and industries than could otherwise exist. The argument has been used that if each generation do not permit themselves to mine a resource in order to conserve it for future generations then no generation will receive the benefit of that resource (Barnett *et al* 2010) and little thought given to preserving other non-renewable resources such as oil, gas and minerals for future generations. However in deciding to exploit such a resource, the consequences of progressive decline in storage and natural discharge, outlined above, need to be taken into account, and plans developed and communicated to address the consequences.

Globally, 70% of all water withdrawn from aquifers, lakes and streams is for agricultural production, and the Food and Agriculture Organization (2011) predicted that by 2050 there will need to be 70% more food production globally to sustain the growing population and hence a need for much more effective policies for land and water management. Not only is demand increasing, but rainfall and recharge to groundwater is expected to decline in many semi-arid areas that depend on groundwater for irrigation (Kundzewicz *et al* 2007).

Notwithstanding the global storage decline, in some local areas groundwater levels are rising causing waterlogging or soil salinisation problems. Examples include in areas where surface water irrigation occurs and the rate of groundwater mound dissipation is slower than the groundwater accession rate beneath the irrigation area. Conjunctive use of surface water and groundwater is proposed as an effective management strategy in such areas, eg in a number of canal-fed irrigation developments in India (eg Uttar Pradesh) where substitution of groundwater for some supplies has restored groundwater levels. Garduño *et al* (2011) report the case of Uttar Pradesh in the Ganges alluvial valley where 50% of the area is suffering groundwater decline due to intensive irrigation and 20% is threatened by a rising shallow water table in the vicinity of surface water irrigation canals. In these areas a conjunctive use approach that includes reducing seepage from leaky channels , improving canal operations, encouraging tube wells in high water table areas for groundwater irrigation, and investing in soil salinity and sodicity mitigation is implemented. This is anticipated to increase cropping intensity through reducing sodic.land problems while sustaining groundwater,

In areas where land use change has been extensive, such as clearing of forest or other deep-rooted perennial vegetation, increased recharge due to lower evapotranspiration may raise the water table and cause waterlogging in humid areas or soil salinisation in semi-arid areas. In land with low topographic relief and extensive aquifers it is clear that no individual farmer acting alone could solve the problem. „Land Care“ a grass-roots collective movement among Australian farmers and agricultural research and extension officers has been highly effective in identifying natural resources management problems, building capability to select and implement solutions, including revegetation, and to monitor changes in groundwater levels, ecosystem health, biodiversity and agricultural productivity in an adaptive community-wide approach (Government of Australia, Department of Agriculture, Fisheries and Forestry 2008). Actions by Land Care Groups are generally resourced by group members and

competitive government natural resources management grants. A national awards program recognises the most conspicuous achievements.

## 2.2 Groundwater management objectives

Objectives for groundwater management relate to maximising economic utility of aquifers while sustaining the environment and providing security for meeting human needs (Fig 2). This simple statement reveals the crux of the groundwater management issue. Utility or value of groundwater use varies with time depending on the time series of annual or seasonal volume of water recovered, and the unit contemporary economic and social value of the uses of that water. Managing groundwater to maximise utility therefore depends on the discount rate used to value future uses. In some arid areas, groundwater irrigation at unsustainable rates has been part of an intentional plan to help rural populations to transition to an economy that is less water-dependent (Moench *et al* 2005).

In its simplest form, maximising utility over the time period of one or two electoral cycles and disregarding future values would always lead to resource depletion. If groundwater resource levels and ecosystem and economic functions are to be preserved so that the aquifer can continue to be used by future generations, then a very low discount rate should be used for decision making about temporal patterns of abstraction. It is also evident that where the aquifer is used for only the highest valued uses, the economic utility of groundwater use will be maximised. That is, it is possible, that reducing abstraction but for use only on the highest valued uses can increase the utility of groundwater use. This model also implies the value of collective management of all abstraction from the aquifer. Where there is no constraint on volume or type (value) of use, the utility of the resource will be smaller than where management is effective. The costs of management are presumed to be small with respect to the consequent increase in utility for the community, as revealed by numerous case studies (eg Foster *et al* 2011).



Figure 2. Aquifers have a range of attributes for which they are valued. Consideration of irrigated agricultural production needs to first take account of other more enduring and potentially more valuable functions, in addition to a holistic view of the availability and function of other potential sources of water.

Groundwater mining is a strategy where current resource use for economic gain takes precedence over not only potential future uses, but also over immediate impacts on groundwater dependent ecosystems. This strategy should also take account of the decline in flow in any connected surface water systems, with consequences to water users reliant on those systems. Transitional arrangements may include switching from groundwater supplies to new alternative supplies. Already treated sewage effluent can be economic as a substitute water source, such as in the vicinity of Mexico City. However, care is needed to ensure groundwater quality protection through adequate treatment and informed irrigation

management. To date, and for the foreseeable future, the cost and energy requirements of seawater desalination are likely to be prohibitive for crop irrigation.

An overarching integrated water management framework, where groundwater is one of the sources to meet the range of uses, taking into account the quality being fit for purpose, suggests that optimal utility of integrated water management will exceed that for managing groundwater independently. Furthermore the characteristics of groundwater storages can be a major advantage when integrated with other systems. For example, groundwater may be most valuable as a drought and emergency supply, taking account of its reliability, protection from evaporative losses and consistency of water quality in comparison to surface water sources. Hence, integrated management, in some cases will be most efficient through interventions to replenish groundwater in periods of excess surface water availability. This practice, known as managed aquifer recharge, has to date been used largely by groundwater users to augment groundwater resources, but has rarely been considered by water resources managers as part of integrated water management strategy.

### 2.3 Conventional groundwater management methods

Evidently, in general, our current models for groundwater governance are unsuccessful in restricting groundwater depletion and also fail to stop the accelerating rate of depletion. Either the current benefits of groundwater overexploitation are seen as outweighing the current and future costs of depletion, or else governance processes are failing to observe the status of systems, develop effective plans, engage with communities and stakeholders, implement reform or combinations of these measures.

Practices commonly applied involve groundwater resource assessment and demand management (Box 1). There is no substitute for having adequate scientific assessment of groundwater resources, (eg Pavelic *et al* 2011 water balance studies in West Africa). However resource assessment is often initiated after it is appreciated that there is a problem with falling water levels. This means that there is entrenched investment in groundwater use that exceeds long term supply and creates environmental detriment. This makes demand management problematic. Hence resource assessment at an early stage with dissemination of information would be an important step forward as a preventive measure (Fig 3).

Demand management can take many forms. The simplest is *laissez-faire* management or "let the aquifer decide". Groundwater users take whatever they can from a depleting aquifer, leading to intermittent and inadequate supplies, high groundwater pumping costs, and wasted investment if the crop cannot be brought to maturity or industry closes. High valued uses such as drinking water supplies may be denied to sectors of the community who lose access to groundwater for lower valued uses. Demand will shrink to those who can afford to extract groundwater. The decline will be disorderly, disruptive, divisive and painful for many.

**Improved water use efficiency** can also be an important part of reducing demand, if this does not also result in expansion of irrigation area. More „crop per drop“ can also be achieved through improved agricultural knowledge and practices, including mulching and fertility, giving consideration to crop selection, timing of planting, improved irrigation methods, and discontinuing irrigation on soils that are unsuitable. These can potentially increase farm revenue while reducing groundwater consumption. Motivation can also involve water or energy pricing to discourage profligate use and to reflect actual costs of supply.

Systems where **entitlement to ground water is linked to land ownership** have very similar consequences to *laissez-faire* management . While land ownership gives a very simple system of rights there is no assurance that supply can be sustained at the capacity of the land for growing crops. In fact in semi-arid areas it is highly likely that extraction would exceed all recharge through the land surface of the property. Furthermore, some or all of

that recharge would previously have contributed to groundwater discharge to streams and groundwater-dependent ecosystems. So even constraining the right of the landholder to extract all recharge from their property would ensure environmental degradation.

*Box 1. Elements of effective groundwater management plans*

*Resource assessment*

- Require drillers to have training and adhere to standards (licensing drillers)
- Require geological or drillers logs, yields, water samples, and water levels of all new bores to be recorded and submitted to a government data base
- Install observation wells to help reveal the initial status of the resource in locations where groundwater use is likely to increase
- Record groundwater levels and groundwater quality in observation wells
- Record estimated aggregate use from existing wells
- Record status of springs and groundwater dependent wetlands
- Groundwater resource assessment to estimate natural recharge and discharge and impacts of various future levels of exploitation

*Demand management*

- Improve irrigation efficiency
- Select crops with lower water requirements
- Pricing of electricity or water should reflect costs of supply and encourage conservation
- Restrict proximity of new wells to existing wells and groundwater falajs (reducing interference)
- Restrict proximity of wells to environmentally sensitive natural groundwater discharge zones with high conservation value
- Restrict depth of wells (used to self-constrain extraction) for various types of wells, (eg drinking water supply wells may be deeper than irrigation wells)
- Record crop areas and restrict the maximum area of crops irrigated by a well
- Fit cumulative flow meters to wells and monitor
- Periodic revision of groundwater resource assessment informed by monitoring data, groundwater use information and further hydrogeological investigations
- Prepare a groundwater resources allocation plan for community consultation
- Farmer-led groundwater management (generally where systems are not already over-exploited)
- Assign groundwater entitlements as shares in the resource, subject to conditions of use
- Allocate groundwater extraction constraints with compliance monitoring
- Develop groundwater trading arrangements for entitlements and allocations
- Periodically revise plans and allocations

*Groundwater replenishment (managed aquifer recharge) or supply substitution*

- Identify and test options for enhancing groundwater recharge and evaluate alternative supply options for recharge or to replace groundwater use
- Include provision of managed aquifer recharge and alternative supplies in groundwater resources allocation plan for community consultation
- Assign groundwater recharge entitlements as shares in the replenishable volume, subject to operating conditions
- Assign recharge recovery allocation rule (to the environment or to groundwater users based on recharge operations and who invested)
- Build, operate and monitor managed aquifer recharge projects, resourced through sale of recharge recovery allocations or through government support of groundwater management
- Maintain records for recharge credit allocations

- Periodically review of rules and performance as part of the water allocation plan for community consultation

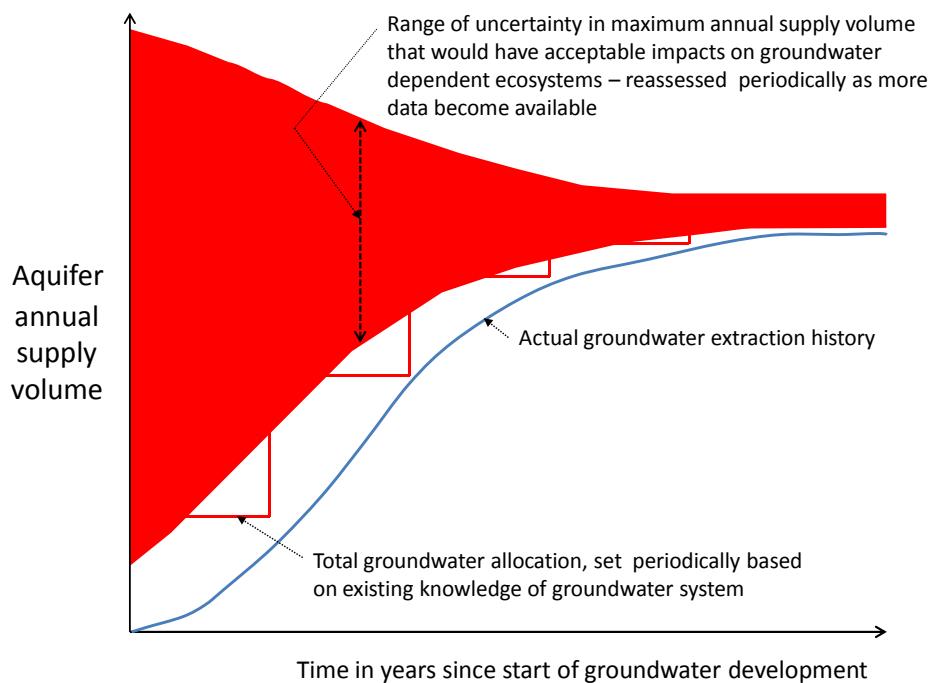


Figure 3. Groundwater resource assessment at an early stage may be crude but it does provide a basis to establish a groundwater allocation system to avoid over-exploitation. As more information become available during groundwater development the uncertainty in aquifer response reduces and groundwater allocations are periodically adjusted. Upwards adjustments are very easy to accommodate, however downward adjustments are difficult. Hence initially conservative resource allocations would be wise.

In addition, evaporative concentration of solutes in applied water would result in chronic groundwater quality deterioration. Furthermore, there is no assurance that water use will be for the highest valued uses, especially where soils are variable and support different crops with quite different economic returns per unit volume of water irrigated. The concept of a groundwater system being divided into fenced parcels with independent ownership is as absurd as the notion that a landholder would own migratory birds that rested on their property.

Entitlements have also been allocated in the order of sequence of exploitation, that is, a ***prior rights system***. However, this also entices over-exploitation. An astute land holder aware of the value of groundwater would logically aim to be first to create wealth through as much irrigation as possible in order to have established a prior right to that volume of water. As soon as neighbours see the benefits of groundwater use there is a race for groundwater consumption to secure entitlement. Subsequently, when the system is clearly over-allocated, the last users are denied an entitlement to extract groundwater and the resource allocation is monopolised by earliest users. As with land-tied water entitlements, this constrains the utility of the aquifer whilst ensuring inequitable allocations. Prior use systems have been well intentioned to protect rights of native American Indians in some states of USA, but rarely do they account for environmental uses of groundwater, such as ecosystem support. Supplemental measures, such as early groundwater laws in Nebraska in 1957,

covered the registration of irrigation wells and set a minimum well spacing of 200m to reduce conflicts between groundwater users.

A **centralised system of consumption constraints** has also been attempted in a number of places. This is when a government authority defines the total allowable volume of water consumption and then applies this by pro-rata, or some other method to assign allocations to individual users. This can be accompanied by compulsory installation of meters on wells, or by regular survey of the area under crop to determine compliance. Such non-consultative attempts to constrain groundwater use have resulted in poor levels of compliance, penalties for farmers, expensive monitoring and litigation, increasingly complicated governance arrangements (eg accounting for carry-over of unused allocations), and a perpetual chasm between groundwater regulators and groundwater users, and conflicts between users. A combative approach means future adjustments to allocation are also met with resistance and groundwater management becomes politically charged.

In relation to the regions where groundwater storage decline are greatest, Table 1 gives a view of storage decline (Konikow 2011) and relates these to the dominant groundwater entitlement systems applied and their projected capability to manage depletion. Irrigation is the dominant groundwater use in every case. In essence Table 1 confirms that groundwater title that is attached to land ownership is a failed experiment and needs to be abandoned in favour of more innovative approaches that are described below.

Table 1 Dominant groundwater entitlement systems and groundwater uses in relation to groundwater storage decline

Region	Mean annual storage decline 2000-2008 (km <sup>3</sup> /yr)	Dominant groundwater entitlement system based on:	Current groundwater storage projections	Dominant groundwater use
USA	25.5*	Land ownership or prior rights	depletion	irrigation
Northern India	52.9*	Land ownership	depletion	irrigation
Saudi Arabia	13.6*	Land ownership	depletion	irrigation
North China Plain	5.0*	State ownership but licensing ranges from comprehensive to effectively unlicensed	sustained production to depletion	irrigation
Nubian Aquifer	2.4*	Land ownership	depletion	Irrigation & city supplies
NW Sahara	2.2*	Land ownership	depletion	Irrigation
Australia	<0.3**	State ownership and water access entitlement	sustained production	Irrigation, stock and domestic
Philippines	<0.1**	Shared use of common pool resource	sustained production	Irrigation

\* from Konikow (2011); \*\* estimated

## 2.4 Innovative groundwater management methods

However there is good news. There is an increasing variety of groundwater governance methods including cap and trade systems, managed aquifer recharge and substitutional supplies that provide groundwater managers many more degrees of freedom in order to bring groundwater systems into equilibrium while minimising costs or even increasing production. There are also excellent examples of communities with groundwater systems in decline who have implemented effective strategies and have reversed groundwater depletion and re-established desired equilibrium conditions.

Community engagement and building institutional capacity allow holistic solutions tailored around community needs (Moench *et al* 2005). Such interventions generally address multiple connected issues, such as health, livelihoods, environment, and in acting to resolve shared groundwater problems community cohesion and wellbeing are enhanced. Technical capabilities to assess hydrologic balance, improve irrigation efficiency and crop selection, enhance groundwater recharge or develop substitute supplies will be required. Importantly institutional capabilities to influence supply and extraction, to build and maintain infrastructure and to finance such activities are also necessary and generally evolve from existing community cooperative arrangements and structures (Wegerich 2005).

The ongoing good news is that these actions can occur at decentralised level by motivated communities, with technical support, without necessarily waiting for national or state policy reform, although this would certainly expedite more broad-spread effective action and make technical expertise more accessible. There are many outstanding examples of localised collective actions to resolve issues with reducing and insecure supplies (eg Government of India Ministry of Water Resources (2012) and Garduño *et al* (2011). A selection of these are summarised in section 3.

As an introduction to additional innovative strategies, a brief description of the state of the art in groundwater allocation (demand management), groundwater recharge enhancement and substitutional supplies is given below with examples provided in section 3.

A **decentralised system of entitlements and allocations** has been employed in recent years in various jurisdictions. This involves determining the total volume of groundwater extraction considered acceptable or sustainable. A water allocation plan is then devised in partnership with the community to determine the proportion of this volume to which each groundwater user may have an entitlement. That is like shares in a stock-market and if the volume deemed to be available for allocation is adjusted, based on a scientific assessment, the volumetric allocation is automatically determined based on the predefined entitlement share. The distinguishing feature is that entitlements are awarded on the basis of community support on the method of allocating shares and that shares are then allocated in a defensible way. This may require, at the community's request measurements via meters or land use maps and satellite imagery. It is important to note the separation of processes between determining shares or entitlements, and determining allocations (Young and McColl 2003). That is the contemporary volumetric allocation is based on the individual's defined share in the resource and the latest scientific assessment of the volume available for allocation. Note that while this method overcomes the fractious nature of centralised allocations, but on its own it does not ensure that water is used for the highest valued uses.

Where excess surface water resources are available, even intermittently, it may be more economic to recharge groundwater than to forego already efficient irrigation production.

**Managed aquifer recharge** is the term describing the increase in groundwater recharge over what would have occurred naturally, as a result of interventions designed to enhance groundwater storage and quality. That is groundwater managers can evaluate supply side as well as demand side options. In some locations it may be more efficient to replace groundwater supplies with a surface water distribution system to reduce demand on groundwater. That is **substitutional supplies** may be an effective way of meeting the need for irrigated food production while sustaining groundwater. Conjunctive use of groundwater and surface water may be helpful in preventing waterlogging in surface water irrigation areas.

### 3. Elements contributing to successful management of groundwater storage

Innovative methods for groundwater management to complement and augment or replace traditional methods include a more flexible approach to demand management, as farmer led management (for aquifers that are in storage equilibrium), a cap and trade system, and supply side measures of managed aquifer recharge and substitutional supplies. These are described in turn below.

#### 3.1 Management by groundwater user collectives

In aquifer systems that are not over-allocated the management options expand greatly, and the tension in implementing them is low. **Farmer-led management** such as in the northern Philippines (Dillon *et al* 2009b) has been implemented with technical support and training by the Philippines Bureau of Soil and Water Management in two communities overlying coastal aquifers where groundwater use for irrigation has been expanding. The program has been highly successful, leading to improved crop selection related to soils, improved irrigation efficiency, increased yields, community-based groundwater monitoring and evaluation, collective decision making concerning crop planning taking account of the status of groundwater storage, and greater knowledge of the aquifer, the consequences of excessive use, and implementation of well-head and groundwater quality protection measures, concerning fertilisers and wastes. Farmer Water Management Schools provide an effective model that can be extended to other groundwater irrigation areas.

#### Box 2. Curriculum of Farmer Water Management School, Ilocos Norte, The Philippines

- Module 1 - Knowing weather and climate as an important tool to develop cropping pattern and calendar
- Module 2 - Operation and maintenance of pump and engine sets
- Module 3 - Soil management
- Module 4 - Hydrologic cycle and understanding groundwater supply
- Module 5 - Groundwater movement and quantity
- Module 6 - Groundwater quality and contamination
- Module 7 - Groundwater balance (recharge and discharge)
- Module 8 - Introduction to crop planning
- Module 9 - Integrating groundwater balance and crop planning
- Action planning session
- Exhibition & graduation

Source: Philippines Bureau of Soil and Water Management



(a)



(b)



(c)

Farmer water management school activities at Pasuquin, Philippines: (a) Pump operation and measurement of discharge; (b) Field day and exhibition stations manned by FWMS farmers; (c) Recording monthly rainfalls and groundwater levels. (*photos by Samuel Contreras, Philippines Bureau of Soil and Water Management*).

**Box 3. Andhra Pradesh Farmer Managed Groundwater Systems, India**

Andhra Pradesh Farmer Managed Groundwater Systems (APFaMGS) was an FAO supported project aimed at improving the water use efficiency by empowering farmers in monitoring and managing groundwater resources in their hydrological unit. The project developed people's institutions for groundwater management, augmentation of groundwater resources through recharge enhancement and promotion of sustainable agricultural practices. It was conducted in the state of Andhra Pradesh, in southern India, and spread over 638 villages in seven drought prone districts.

More details of the methods and achievements of this project which focussed on empowering self-imposed demand management supplemented with recharge enhancement where warranted are at <http://www.fao.org/nr/water/apfarms/index.htm>



Measuring and recording hydrological variables. The project subtitle was “Demystifying science for sustainable development”.

**Box 4. Integrated natural resources management at village level in a drought prone area (adapted from Garduño et al 2011 and Government of India, Ministry of Water Resources 2012b)**

Hivre Bazaar is a village of 1,200 people in a semi-arid (450 mm/yr average rainfall) and drought-prone elevated part of the Deccan Traps Basalt of Maharashtra, in western India. Agriculture is the mainstay of the economy with staple crops grown for home consumption or used as livestock fodder or domestic fuel, while most pulses, onions, vegetables, and flowers are sold at market. Up to 60% of land can be irrigated in years with good monsoonal rainfall but in the 1989/90 drought this fell to less than 5% and all village wells ran dry.

Led by an informed and charismatic Village Council Chief, a concerted effort on catchment and groundwater management and agricultural reform began in 1994. The Village Council acted to:

- (i) prohibit the use of tube wells for agricultural irrigation,

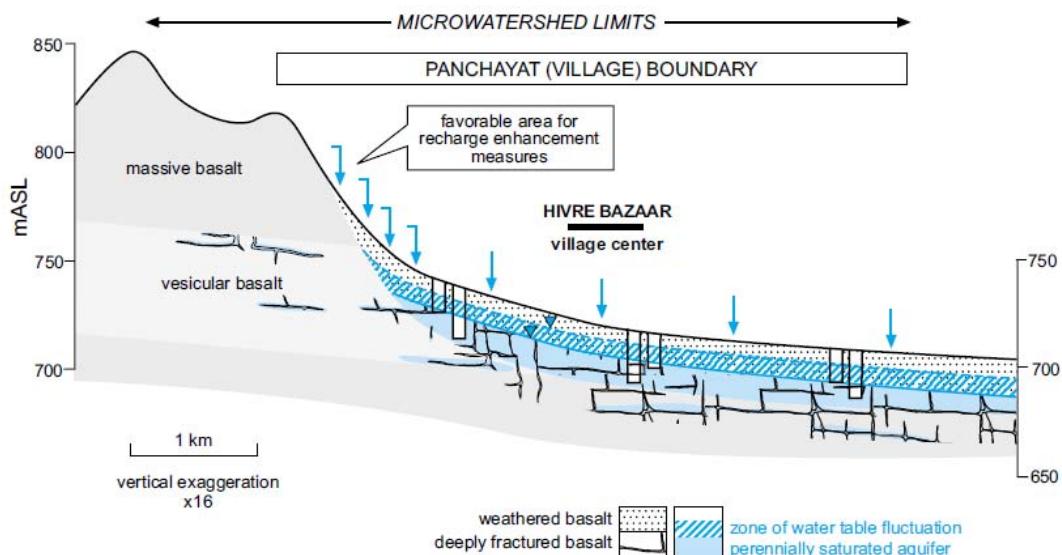
- (ii) implement micro-watershed soil and water conservation; and
- (iii) ban sugar-cane cultivation.

...(Box 4 continued)

These measures, implemented in a comprehensive 5-year plan, had the effect of diverting farmers resources away from unproductive competition for scarce deeper groundwater water, to water conservation and recharge enhancement for the shallow (up to 15 m bgs) weathered-zone aquifer. Extensive effort went into hill contour trenching and stream bunds. Reforestation assisted by a livestock grazing ban restored degraded land, reduced erosion, improved the quality of water and reduced low valued irrigation requirements. Sugar cane had high water use and banning its growth also eliminating distilling practices and socially undesirable consequences. Improved crop selection maximised the value of irrigated crops.

Village-level crop-water budgeting was introduced in 2002 and in dry years villagers are asked to reduce their proposed irrigated area and to give preference to low-water demand crops. Mutual surveillance is usually sufficient to achieve compliance. Such proactive groundwater and agricultural management has resulted in a marked contrast between Hivre Bazar and most surrounding villages.

The consequences were remarkable. Household incomes rose markedly (to over US\$500 per year on average), and land values appreciated many-fold in the past 15 years. Drought resilience and income security has increased and farmers no longer need to leave the village to search for paid work in dry years. Degraded land has been restored and made productive. As many as 32 dugwells produce important revenue in the dry season from irrigated onion, vegetable, and flower cultivation, and only a few in the upper watershed dry out.



Simplified hydro geological section of Hivre Bazaar micro-watershed methodology of study  
(from GWMATE 2009)



Hivre Bazaar (a) catchment before intervention, (b) a percolation tank for aquifer recharge, (c) consequent productive irrigated agriculture. (Sources from various Hivre Bazaar websites).

### Box 5. Example of management by groundwater user collectives in Spain

Since the mid-20th century the expansion of irrigation from “Los Arenales” aquifer, located in Castilla y León, Spain, has led to decline in groundwater level of more than 20m. The Aeolian sand aquifer, with an area of 1500 km<sup>2</sup> and thickness up to 55 m is also very vulnerable to drought (MAPA, 1999). In order to mitigate this impact, the Spanish Ministry of Agriculture (MAPA) developed Managed Aquifer Recharge (MAR) facilities in three pilot zones. These were accompanied by improvements in water management, based on the organization of communities of irrigators, exchanges of arable land, changes in crops, improved efficiency of irrigation and reduction of energy consumption. Also there was recovery of environmental features such as degraded wetlands (La Iglesia and El Sefor lagoons), springs that had dried and dilution of nitrates and of other pollution.

River water was diverted for recharge (respecting evaluated ecological flow) by gravitational flow through 18km of buried pipes to the recharge facilities, including infiltration ponds, artificial wetlands, canals and large diameter wells. Some years later, researchers successfully tested buried filter pipes and drainage ditches (Fernandez, 2010a). Once constructed and commissioned, the works were transferred to the communities of irrigators, who are responsible for the management and maintenance, under the advice of specialists of the Duero Hydrographic Confederation (CHD). Due to variable river flows annual volumes recharged in the two main experimental pilots ranged between 0.5 and 12.2 Mm<sup>3</sup> (Santiuste basin) and between 0.5 and 5.5 Mm<sup>3</sup> (Carracillo council) between 2002 and 2008. The river water was supplemented by 0.5 Mm<sup>3</sup>/year treated sewage effluent since 2005.

Initially some farmers resisted the new organizational structures and this was resolved through negotiation. DINAMAR implemented "The Water Ways", a process of informing the community on sustainable development, environmental awareness and hydrogeological processes including applications of Managed Aquifer Recharge (in Fernández 2010b). Subsequently there has been an unintended increase of about 15% in the irrigated area due to what has been called “contagious effect”, of a decline in the price of water and in the costs of pumping. Incipient economic resurgence is observed in these rural areas that had previously been depressed. Of concern is the growing demand for irrigation supplies in areas that are not so feasible for MAR. Innovative approaches will be needed to achieve collective solutions to these problems.

This experience is a significant example of public participation, first as the trigger that stimulated the construction of MAR facilities by the Spanish Government, and importantly as groundwater users increased their productivity and water management efficiency. This also demonstrates integration of recharge enhancement with demand management. There is also a new shared perspective of the aquifer as both an irrigation resource and sustaining the environment. Organizational change has motivated a substantial environmental improvement and will provide a basis for resolving emerging issues.

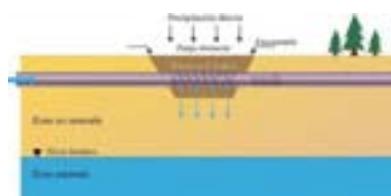


Diagram of recharge basin on pipeline from river that recharges groundwater



Water from wastewater treatment entering recharge ditch



Water replenishing wetland

**Box 6. Example of agronomic water conservation measures in central Punjab (*adapted from Garduño et al 2011*)**

In Punjab 70% of the irrigated area is dependent on groundwater delivered by 2.3 million farm tube wells with electric submersible pumps. Rice growing was resulting in groundwater net deficits of 120-180mm/year. Groundwater tables were falling at 0.6 to 1 m/yr, many wells were being deepened, and the state government was underwriting soaring energy costs.

In response, in 2008 the state government issued an ordinance prohibiting transplanting of paddy rice until June 10, the start of the monsoon, and up to 40 days later than the usual practice. This eliminated an estimated 90mm of non-beneficial evaporation and 175 million KWh electricity consumption without impacting on crop yields.

This was highly successful, with more than 95% farmers compliant because violations were highly visible and severely penalised. Additional measures were incorporated in the Punjab Preservation of Sub-Soil Water Act of 2009 including laser levelling of fields, soil moisture based irrigation timing for winter wheat, and improved faster growing rice varieties to minimise irrigation requirements. Water level responses are being monitored to determine the impacts of these policy changes, which are expected to prolong the groundwater resource by reducing the deficit by 50 to 65%.

### 3.2 Cap and trade demand management

**Cap and trade systems** are designed to allow exchange of entitlements and/or allocations among groundwater users, including new entries. Trading systems are set up to allow water to be transferred from lower to higher valued uses, subject to environmental conditions. This increases the utility of the aquifer. The user with a higher valued use of groundwater can afford to buy an entitlement (long term share) or an allocation (volume of water in the current water accounting period) from a user who may receive more for their allocation than they would from the net return on the crop they could grow on their soils with their resources. Hence this can be a win-win-win situation where both parties and the community at large benefit from the reallocation of the resource. Constraints on trade may include that allocations cannot be traded further down-gradient in established groundwater cones of depression, or towards groundwater dependent ecosystems or hydraulically connected streams. There may also be constraints on exchanging fresher groundwater for more saline groundwater as the average salinity of the aquifer may increase. Also consideration would need to be given to preventing trading of „sleeper” entitlements (entitlements held on paper but not actually used), as otherwise groundwater extraction from the aquifer would actually increase. A cap and trade approach also gives the government the option of buying entitlements on the water market on behalf of the environment.

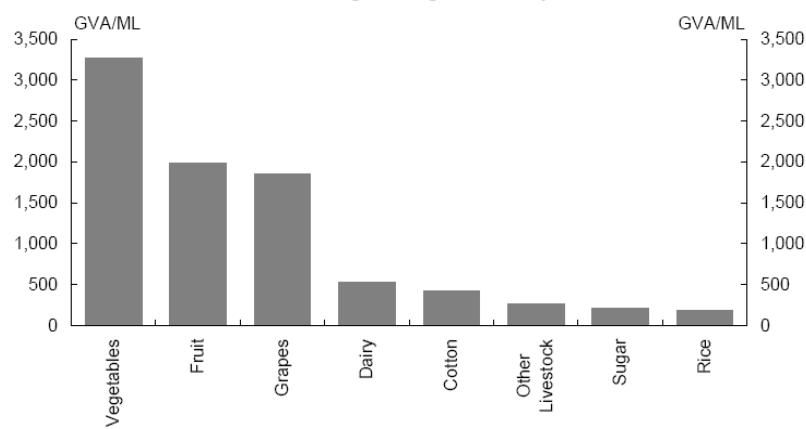
Cap and trade systems can be used with any prior entitlement allocation system that is over-allocated. A volumetric discount may be assigned to the traded allocation so that the aquifer could potentially reach hydraulic equilibrium through groundwater trading. The traded allocation would of course need to be divorced from any land or prior rights. Allowing trading could also be accompanied by substitution of shares in the allocatable pool to replace volumetric allocations to all groundwater users, as a way of addressing the longer term needs for sustaining the resource. While trading would give a windfall commercial gain to already privileged groundwater users, it could provide the inducement needed to establish a management regime that would lead to a more secure and resilient aquifer and increase the stream of future benefits. It is essential that groundwater allocations are capped for aquifers hydraulically connected to surface water systems that are capped.

**Box 7. Example of water-trading in the Murray-Darling Basin, Australia**

In the Murray Darling Basin of Australia surface water trading takes place within a cap. The gross value added per megalitre ( $1000\text{ m}^3$ ) of water used for irrigation varies over an order of magnitude from rice (<\$200/ML), livestock, cotton and dairy up to grapes (\$1800/ML) and fruit crops and is maximised for horticulture (\$3200/ML). See fig from Roberts *et al* (2006) below. This suggests there is significant potential to increase returns, or to secure returns for fixed-rooted crops, by trading between water users and gross utility could be enlarged even with reduced water use. Note that this is gross value not net value at the farm gate, against which price of water would be compared by the irrigator considering selling or buying an allocation. At around this time the price of temporary allocation trading of water in the Southern Murray Darling Basin varied from \$80 to \$700/ML, subject to the scarcity of the surface water resource (Kaczan *et al* 2011) and traded allocations totalled 20,000 ML/yr. It is important to ensure that a groundwater cap is in place to prevent substitution of groundwater for surface water. These systems should be assumed to be hydraulically connected unless proven otherwise, and managed in an integrated manner.

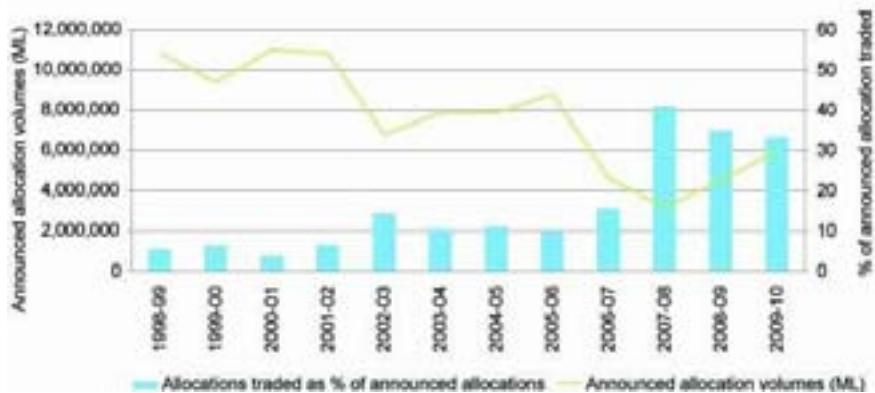
In over-allocated groundwater systems, water allocation plans are expected to increase recognition of the state of scarcity and influence price on the water trading market. Noting the volatility of the surface water market, managed aquifer recharge could play a valuable role in conjunctive management of surface water and groundwater in systems that are capped.

**Chart 3: Gross value added per megalitre of water used in irrigated agricultural production<sup>12</sup>**



Source: ABS, 2004.

*Value of water uses from Roberts et al (2006) (units A\$, 2004)*



*Water allocation volumes and water sales as a percentage of water allocated in the southern Murray-Darling Basin from 1998/99 to 2009/10 (from National Water Commission 2011a).*

**Box 8. Groundwater-trading in Australia – National Perspective**

Groundwater trading in Australia in 2010–11  
(adapted from National Water Commission 2011b, p68-69)

Jurisdiction	30/6/11 Entitlement	Traded Entitlement Volume (GL)	Traded Allocation Volume (GL)	Traded Entitlement (%)	Traded Allocation (%)	Number Entitlements	Number Traded Entitlements	Number Allocations	Total Number Traded	Traded Number (%)
Qld	1,038	0	2.3	0	0.2	15,264	0	35	35	0.2
NSW	1,934	74.9	31.2	3.9	1.6	74,179	151	155	306	0.4
Vic	863	27.8	4.2	3.2	0.5	10,706	265	70	335	3.1
SA	618	21.4	3.1	3.5	0.5	4,863	172	35	207	4.3
WA	1,772	22	8.1	1.2	0.5	10,562	78	12	90	0.9
NT	131	0	0	0.0	0.0	255	0	0	0	0.0
Tas	0	0	0			0	0	0	0	
ACT	1	0	0	0.0	0.0	144	3	0	3	2.1
Aust	6,357	146.1	48.9	2.3	0.8	115,973	669	307	976	0.8

Entitlements traded are permanent trades of an entitlement to use water. Allocations traded are the right to use water for the period (annual) in which the allocation is traded. The original groundwater title holder can sell their allocation in subsequent years or retain it for their own use. The national volume of (annual) groundwater entitlements is similar to the annual surface water allocation from the southern Murray-Darling Basin. However the proportion of groundwater entitlements and allocations traded is only 3% by volume in comparison with 15 to 55% for surface water systems. It is expected that trading will be less dynamic than for surface water systems where allocations are volatile due to strong dependence on recent rainfall, whereas groundwater typically responds to the accumulation of recharge and extraction over a number of years. In some areas, such as the Namoi Valley, NSW, groundwater and surface water allocation trading occur. As yet the synergies between managed aquifer recharge and water banking have not been explored, and it is considered unwise to do so until the surface water allocation is reduced to an environmentally sustainable level (Ward and Dillon 2011).

*An example of a Water Sharing Plan, and groundwater trading to restore the over-allocated Namoi groundwater system (adapted from NWC (2011b, p69-70)*

The Namoi River region in north eastern New South Wales is an irrigated agricultural area where cotton is grown predominantly and also cereal crops, pasture and hay. Surface water is the preferred source but most farms also have access to groundwater which is used more heavily in dry years. On average groundwater use is 49% of total water use but in dry years it can reach 78%. Groundwater levels have been in decline for several decades and in 2006 a Water Sharing Plan was agreed covering 12 zones with differing degrees of water stress. Annual entitlements of 376 Mm<sup>3</sup> surface water and 250 Mm<sup>3</sup> years groundwater were issued. Seasonal surface water allocations are proportional to entitlements and are scaled on the harvestable flow in the river. Trading can occur in entitlements (permanent trade) and allocations (temporary trade).

Groundwater entitlements are being reduced to sustainable levels through the issue of non-tradeable supplementary licenses which reduce to zero over a period of 3 to 10 years depending on the zone. The groundwater allocations traded reached 12 Mm<sup>3</sup> in each of 2005/6 and 2006/7 during a drought when annual groundwater consumption peaked at 206 Mm<sup>3</sup>/yr. In subsequent wetter years groundwater use declined to 136 Mm<sup>3</sup> and trading declined to 6Mm<sup>3</sup> in 2010/11 while corresponding surface water use increased and surface water trading grew to 18 Mm<sup>3</sup>. It is evident that farmers are making use of trading of sustainable allocations to compensate for the decline in the volume of supplementary licences. That is overall groundwater use is declining with water reallocated from lower valued uses to higher valued uses based on trading mechanisms available to farmers under the Water Sharing Plan. I

### 3.3 Managed aquifer recharge

Demand side management has the disadvantage to groundwater users of constraining irrigated crop production to the level supported by groundwater resources, which appears in most groundwater irrigation areas to be a tighter constraint than land and labour. This creates an onus on groundwater managers to justify the need for restraint, against the likelihood of reduced farm income. This is a challenging task especially where users have a legal entitlement to extract more than can be supplied by the aquifer in the long term. Hence a „two-handed“ approach, demand- and supply- side management can be very useful for groundwater managers.

In areas where there are seasonal excesses of surface water, supply side measures such as managed aquifer recharge (MAR) can protect, prolong, sustain or augment groundwater supplies. As one of a suite of integrated water resources management strategies, this expands local water resources, reduces evaporation losses, and assists with replenishing depleted aquifers. In some circumstances where seasonal surface flows are large and aquifer replenishment is assisted by permeable soils, such as in the Burdekin Delta in Queensland, Australia, it is possible to avoid groundwater demand management altogether. However more usually, the amount of recharge that is economically or technically achievable is less than the annual groundwater deficit and a combination of demand management and recharge enhancement is essential to restore a groundwater system to equilibrium (Dillon *et al* 2009b). In fact in confined aquifer systems, the act of recharge can directly enhance discharge.

There are many methods for recharging aquifers (eg Dillon *et al* 2009a) and these are selected based on the local hydrogeological characteristics, sources and quality of water available to be harvested. Importantly cost per unit volume needs to be competitive with the foregone net benefits of demand reduction, taking into account the costs of managing demand and supply.

As an alternative to recharging the aquifer, groundwater supplies can be augmented or replaced by surface water supplies, such as canals and pipelines. This has the effect of reducing demand on the aquifer, but is perceived by groundwater users as a supply augmentation. In some places this is misleadingly called „virtual recharge“, but that term is unhelpful when considering groundwater allocation systems (discussed earlier).

The complementary roles of demand management and expanding supplies, either via managed aquifer recharge or by providing alternative supplies are graphically depicted in Figure 4. Surprisingly, recharge enhancement is often left to groundwater users, and governments have tended to focus on demand reduction. A notable exception is the Indian Government through programs such as under the Mahatma Gandhi Rural Employment Guarantee Act, which have supported a very large number of small scale water conservation projects, including managed aquifer recharge, but generally not yet within the construct of groundwater management plans that also constrain extraction. Where surface water is in public ownership and groundwater in private ownership, the act of managed aquifer recharge effectively privitises a public good, so MAR is best implemented where water entitlements are divorced from land ownership. The synergistic effect of managed aquifer recharge on implementing demand management has much potential but is yet to be exploited systematically.

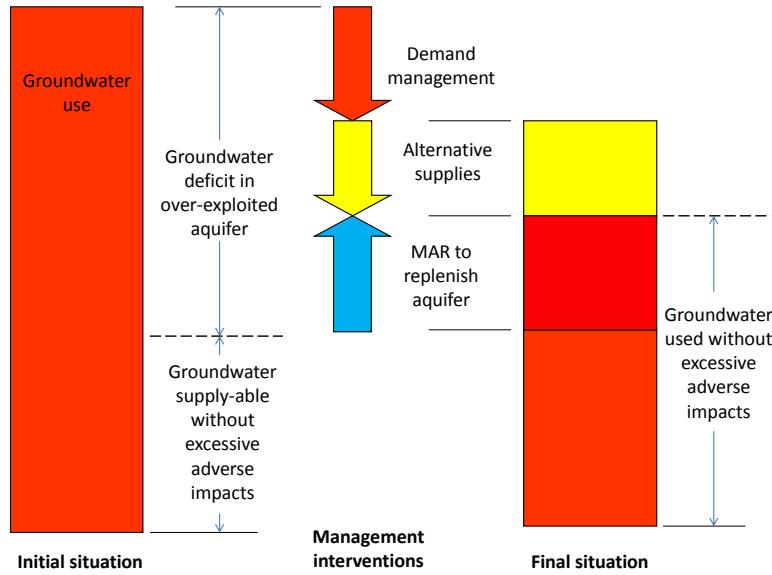


Figure 4. An aquifer can be brought into hydrologic equilibrium by either reducing extraction, or augmenting supplies, either through groundwater replenishment or providing alternative supplies.

#### *Potential for managed aquifer recharge in relation to climate*

In arid climates the lack of availability of a water source constrains the opportunities for aquifer replenishment. Runoff is so infrequent in arid areas that assets need to be cost efficient as they are actively utilised only infrequently, eg. low level recharge dams in Oman (<100mm rainfall) have been highly effective in detaining flash-floods to replenish alluvial aquifers (Fig 5(a)). Managed aquifer recharge is primarily for inter-year storage to increase long term yield. However alternative supplies can also be considered. In UAE a new strategic groundwater reserve is being created in the desert near Liwa to replenish a previously depleted aquifer with desalinated water (flash distillation) that is a byproduct of power generation when needs for power in Abu Dhabi exceed needs for the product water.

Steenbergen and Tuinhof (2009) and Steenbergen *et al* (2011) have reported a wide range of watershed interventions that enhance groundwater recharge, retain soil moisture, and reuse water, which they term the 3R concept for climate change adaption, food security and environmental enhancement. These have been widely applied in arid and semi-arid areas of Africa, Asia and South America with startling results for improving the capability of land and farm income. They may be applied from land-holder scale up to sub-catchment and catchment scale and typically at very low cost and with active stakeholder participation and ownership by the community. The 3Rs encompass managed aquifer recharge and alternative supplies (reuse) in an integrated framework.

In semi-arid climates, water availability is a smaller constraint and seasonal demand for water can be high, meaning that inter-season storage has high value in addition to inter-year storage. Inter-season storage can have immediate commercial benefits. At Cocoa Beach in Florida the aquifer is used to balance season fluctuations in supply and demand for treated drinking water because the cost of an aquifer storage and recovery system is less than 2% of the cost of building more tanks. The well shown in Fig 5(b) can store and recover each year the volume equivalent to 10 times that of the adjacent tank.



(a) Recharge dam, Wadi al Fara, Oman



(b) ASR well, Cocoa Beach, Florida, USA

Figure 5. Some contrasting examples of managed aquifer recharge systems to replenish aquifers

In humid climates, opportunities for natural recharge are greater and the demand for storage is less, so managed aquifer recharge is expected to have a minor or niche role. Figure 6 gives a typology of climatic drivers and constraints for application of managed aquifer recharge. The horizontal axis ranges from arid at left to humid at right. The vertical axis represents seasonality of rainfall, ranging from highly skewed at the bottom to uniform throughout the year at the top. This diagram suggests that demand for water is highest at the left hand side, and demand for inter-seasonal storage is highest at the bottom. At locations where both attributes apply the value of recharge enhancement is maximised, but opportunity for recharge enhancement with natural surface waters are improved where rainfall is higher. From this diagram Darwin is climatically the best suited of the Australian cities for managed aquifer recharge. Interestingly, however managed aquifer recharge has progressed fastest in Adelaide and Perth, because aquifers there are better suited for replenishment.

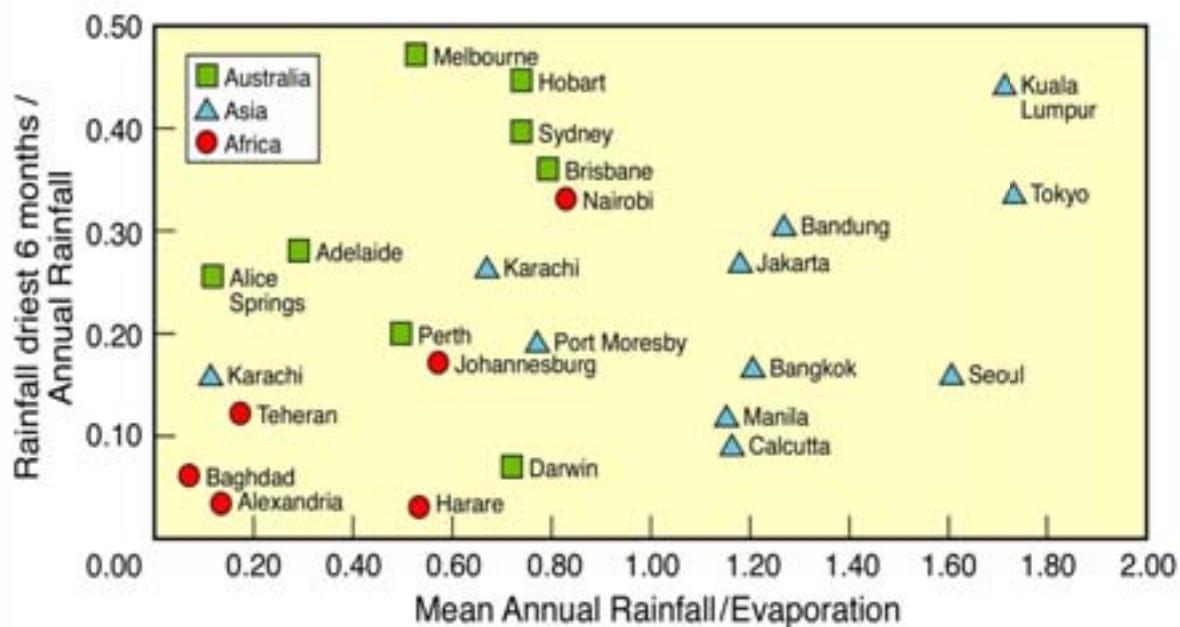


Figure 6. Climatic indicators of favourability for managed aquifer recharge as a water resources intervention strategy include measures of abundance and seasonality of rainfall.

### Potential for managed aquifer recharge in relation to hydrogeology

The characteristics of an aquifer influence its capability for replenishment by managed aquifer recharge and the selection of recharge enhancement method. In general, depleted aquifers unconfined or confined, present the greatest opportunity. Hence managed aquifer recharge may be used as a remedial strategy, but only in conjunction with demand management. It is far better however to use managed aquifer recharge as a pro-active means of preventing depletion than as a restorative measure after problems have occurred.

The attributes of an aquifer impacting its replenishment potential are outlined in Appendix C (from Dillon and Jimenez 2008). Unconfined aquifers are cheapest to recharge and also afford a greater variety of methods to be considered. A range of methods are also shown schematically in Appendix C (extended from Dillon 2005). Consequently it is possible to map the opportunities for managed aquifer recharge based on hydrogeological characteristics. This has been done at national scale for South Africa by Murray and Harris (in South Africa Department of Water Affairs 2010) as shown in Figure 7.

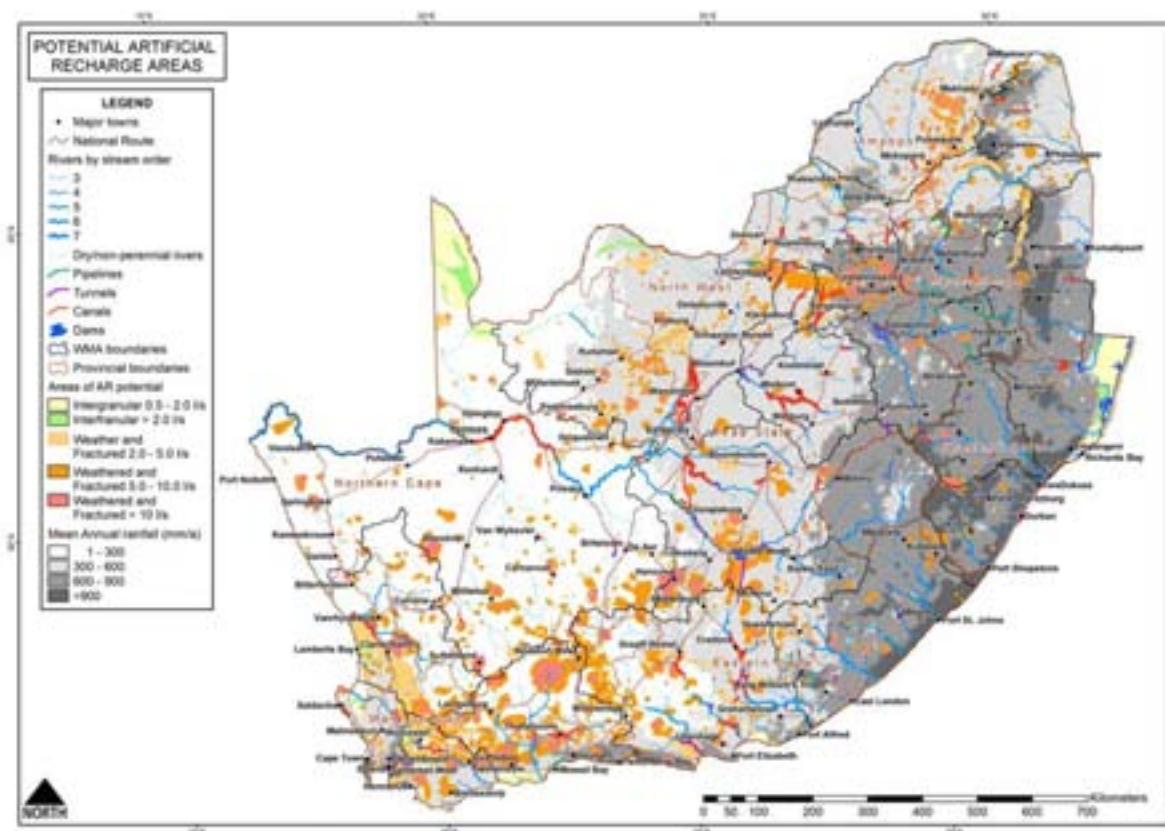


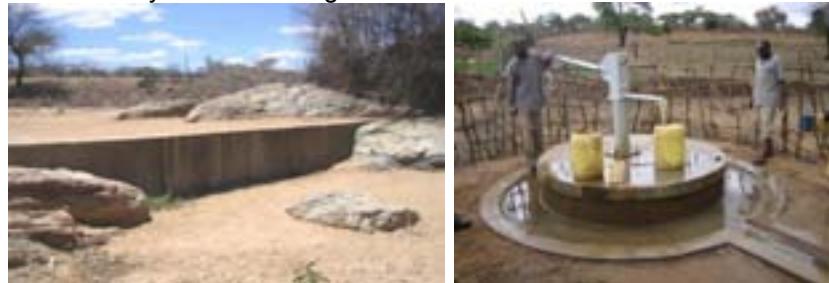
Figure 7 Map showing the potential for managed aquifer recharge based on hydrogeological conditions for South Africa. (from South Africa Department of Water Affairs 2010)

Such maps are only as good as the intensity and quality of data that are used to construct them. They should only be used as a screening method to ascertain the prospects more generally. To assess possibilities in a particular area more detailed local information will be necessary and if information is sparse, further hydrogeological exploration may be necessary before committing to recharge projects and strategies. In Australia, Geoscience Australia has adopted a localised screening model based on well yield (L/s) and salinity.

Sites with high yields and low salinity are preferred. Where there are multiple aquifers, each is mapped and then a composite map of best prospects produced (eg. Dudding *et al* 2006).

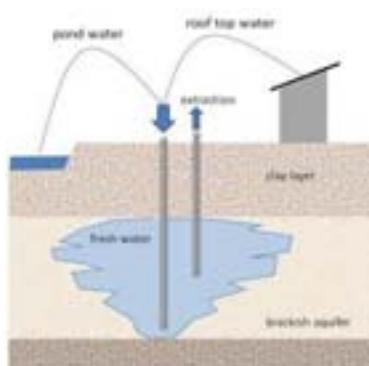
#### Box 9. Managed aquifer recharge in sand dams in Kenya

In the Kitui District, sand storage dams have been implemented on a large scale, and frequently in cascades. A sand storage dam consists of a relatively small dam, built on and into the riverbed of a seasonal river, behind which sand accumulates. The sandy layer acts as an aquifer, which is recharged with river water in the wet season and in which water is retained for use in the dry season. Sand dams are cost effective, they have on average a positive net present value and for one sand dam (25 families) the net increase in family income is  $25 \times 125 = 3,000$  US\$/yr. The total investment cost vary from 10,000-15,000 US\$, and annual maintenance and monitoring cost are estimated at 10% of the investment cost per year. Assuming 2 rainy seasons, the total storage capacity is about 4,000 m<sup>3</sup>/year (Tuinhof *et al*, 2011). With this method a new aquifer, and subsequently new groundwater storage, is created. Moreover, the groundwater level in the area surrounding the sand dam may also increase, replenishing depleted groundwater. The storage provided by the sand dams is enough to provide water throughout the dry season for drinking water and to increase the area with irrigated crops. Sand dams may also provide down-stream benefits as they will reduce the river peak flow and may therefore mitigate downstream floods.



Figure, a. sand storage dam, b. fetching water in Kitui (Acacia Water, 2007).

#### Box 10. Fresh water injection in shallow brackish aquifers in Bangladesh



Bangladesh has abundant rainfall (>1500 mm per annum in the coastal area), but this is concentrated in 3 to 4 months each year during the monsoon. Water shortages are acute during the last months of the dry season, especially in the coastal regions where fresh water availability is reduced by widespread brackish groundwater. In these areas UNICEF in collaboration with the Department of Public Health Engineering (DPHE) has initiated an action research project utilizing the abundance of water in the rainy season, to augment fresh water storage in brackish shallow aquifers.

Four sites were tested in 2011, two with pond water infiltration (Batiaghata and Assasuni) and two with rainwater infiltration. The systems are constructed with locally available material and local manpower. Only a small pump is needed to lift the pond water to filter tank. From there the water is injected by gravity. The testing showed that approximately 700-800 m<sup>3</sup> of water can be infiltrated from the pond system while infiltration rates of sites with only rainwater were ~ 200-250 m<sup>3</sup>.



The salinity data from the pond water infiltration sites clearly illustrate the positive impacts: at the end of the infiltration period the EC in Batiaghata had lowered from 2,600 to 700 µS/cm and in Assasuni from 6,000 to 800 µS/cm.

The economic feasibility shows that the capitalized cost for construction and O&M are US\$ 2- 2.5 /m<sup>3</sup> which is cheaper than alternative solutions such as reverse osmosis and rainwater harvesting in tanks (both > US\$ 8- 10 /m<sup>3</sup>) and water vendors (US\$ 8- 20 /m<sup>3</sup>). 16 more sites will be constructed and tested in 2012 and the feasibility for up-scaling to 100 -500 schemes in the following years will also be completed at the end of 2012.

*Source: Albert Tuinhof, Acacia Institute*

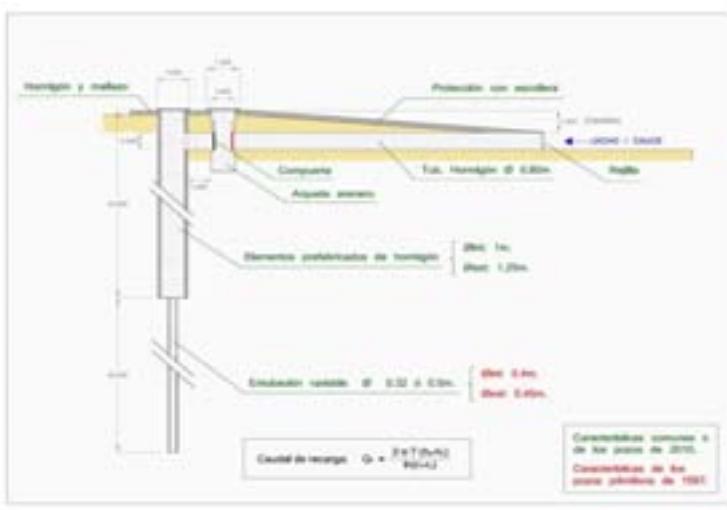
**Box 11. Managed aquifer recharge in Mancha Occidental karstic aquifer, Spain, using wet year flows in Guadiana Channel to offset groundwater overexploitation.**

The Spanish 23th aquifer or UU.HH. 04.04, "Mancha Occidental" is, perhaps, the most emblematic example of over-exploitation of aquifers in Spain. The aquifer has an area of 5,500 km<sup>2</sup> and as a consequence of intense irrigation, the phreatic level has fallen by up to 80 meters and accumulated storage decline exceeds 100 Mm<sup>3</sup>. The aquifer basin also maintains wetlands thanks to its overflow, at "Las Tablas de Daimiel National Park", a Reserve of the Biosphere, and a RAMSAR system of wetlands.

The progressive deterioration of the aquifer and cumulative water table declines were also accompanied by an increase in groundwater salinity, and deterioration of wetlands located downgradient.

Confronted by water scarcity the aquifer was definitively declared as "overexploited" and the Confederación Hidrográfica del Guadiana adopted measures to restore the water imbalance. They built a battery of infiltration wells along the head area of the aquifer in order to store surpluses of water in the wet hydrological years. Therefore, it is an "occasional availability" scheme included in the governance arrangements for flow and management, notably in floods. Twenty five wells up to 90m deep, were drilled in some highly transmissive areas of the karstic aquifer, in three successive campaigns (1997, 2000 and 2010). Wells were distributed over about 30 km along the "Canal del Guadiana", downstream of Peñarroya dam. The good quality of recharge water that is pretreated using filtration and settlement has permitted relatively simple, "low-cost", recharge operations, although there were some problems with air clogging (Fernandez 2010a).

The last cycle of recharge, between January 2010 and March 2011, took advantage of a wet hydrological year and recharge in this period exceeded 50 Mm<sup>3</sup>. The aquifer is still heavily exploited, although impacts are being mitigated through changes in water management practices and improvements in governance schemes. It is a modern challenge to be applied in an area where competition for water has been a traditional source of conflict.



*Diagram of a recharge well and photograph of recharge well gallery under construction near Canal del Guadiana.*



**RAMSAR wetlands supported by the  
Mancha Occidental aquifer**



## **Managed aquifer recharge activities in Tablas de Daimiel National Park**

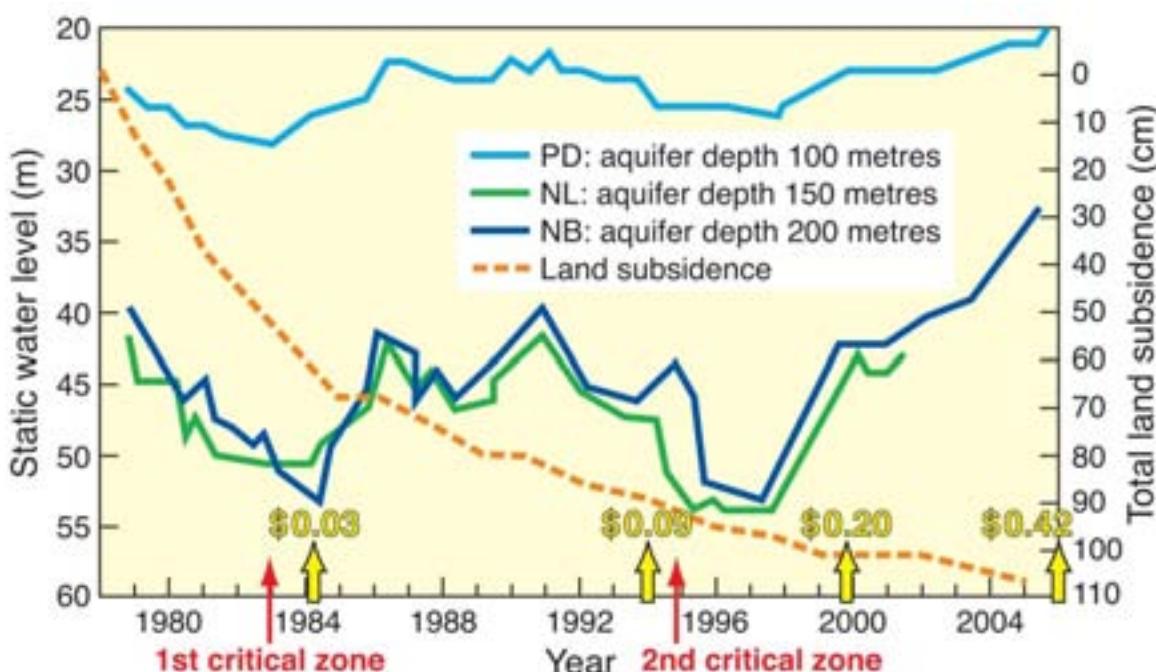


### 3.4 Alternative supplies

Where it is more economic or pragmatic to provide an alternative distribution system to groundwater users than to replenish the aquifer and use existing water supply wells, the most logical solution or combination of solutions should be adopted. Examples of successful recovery of overexploited aquifers include extending provision of surface water supplies to Bangkok (see Box 12) and piping effluent from Mexico City to Mesquital Valley irrigation area. However it is necessary to ensure that these supplies substitute for groundwater use, rather than just augment it in order to regain groundwater equilibrium.

**Box 12. Reversing chronic subsidence in Bangkok by providing substitute supplies and using ground water pricing to modify demand.**

In Bangkok, groundwater extraction for public water supplies and industrial and aquaculture and agricultural uses led to groundwater levels in decline, increasing groundwater salinity deepening spread of pollution, land subsidence and consequent flooding. For many years this was regarded as a chronic intractable problem, as there were so many difficulties for groundwater managers in locating wells, estimating abstraction, implementing a control system and obtaining compliance with the rule of law while the city continued to grow. However the government found a solution through provision of alternative surface water supplies, in key areas of over-abstraction and imposing charges on groundwater use so that surface supplies were cheaper. Groundwater levels recovered and now water pricing policy is used to adjust the balance of groundwater and surface water use so as to keep groundwater levels within their desired range, while covering the costs of water supply and water resources management (Buapeng, 2009).



Groundwater level decline and recovery in three aquifer depths at Ramkamhaeng University in central Bangkok showing the stabilisation and recovery of groundwater levels as a result of groundwater pricing policies that made surface water supplies more attractive. Note that land subsidence rate has declined and stabilised as a result of groundwater level recovery. The times at which prices changed and the price in US\$/m<sup>3</sup> are shown (adapted from Buapeng 2009)

### 3.5 Non renewable resources with lack of alternative supplies

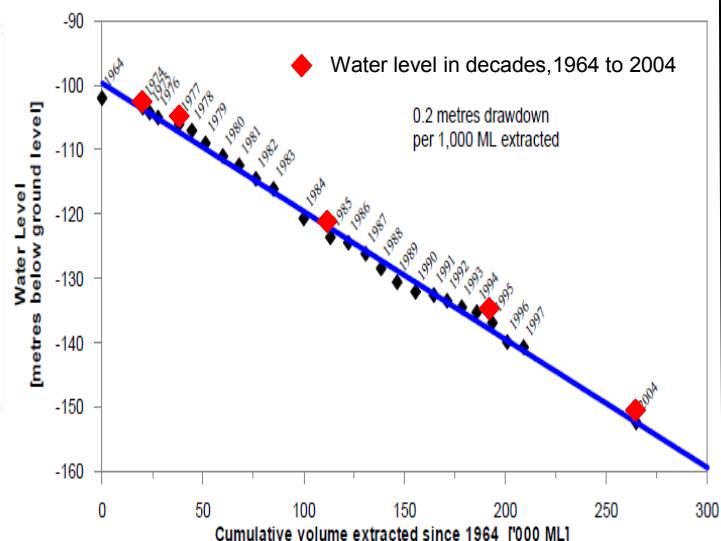
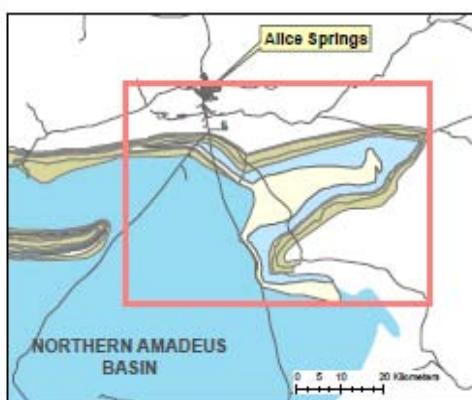
In exploiting non-renewable groundwater resources, the consequences of progressive decline in storage need consideration and plans developed and communicated to address depletion. The costs of accessing the next nearest resource need to be compared with the social and economic benefits of the continued existence in that place of the town or industry. Invariably, minimising consumptive demand has the effect of prolonging the supply and deferring and minimising the cost of accessing remote resources. Box 13 describes a situation where a thriving town is located on a depleting groundwater resource, and the nearest viable alternative water resources are very remote.

### *Box 13. Mereenie sandstone fossil groundwater management plan*

The public water supply for the town of Alice Springs (population 27,000) in arid Central Australia (280mm rainfall and 3000mm potential evaporation) is supplied almost entirely from the Mereenie Sandstone aquifer system of the Amadeus Basin. Groundwater in this aquifer is considered “non-renewable” because the rate of recharge is insignificant compared to the volumes extracted for public water supply.

The Roe Creek Borefield is located about 15 km south of Alice Springs and comprises about 28 production wells drilled to a depth of about 570 m in the Mereenie Sandstone. The fresh groundwater has been dated as between 10,000 and 32,000 years old, indicating a fossil resource recharged during much wetter periods in the past (Barnett *et al*, 2010).

Since pumping began in 1964, about 254 Mm<sup>3</sup> have been extracted with a rate of 8 Mm<sup>3</sup>/year since 1991. As a result, groundwater levels in the Roe Creek area have fallen at a rate of 0.2 m per Mm<sup>3</sup> extracted, from an original depth of 100 m, to about 150 m below ground. The more or less linear rate of drawdown led to the description of a “tank model” (Jolly *et al*, 1994), whereby water is extracted from the aquifer as if from a tank, with virtually no additional inputs from surface recharge or lateral flow.



Location of Mereenie Sandstone aquifer

Drawdown versus extraction (Jolly *et al*, 1994)

The potable water supply aquifer is effectively being slowly mined, and this information was made available to the public in fact sheets and published reports. However, water use was 580 litres per person per day, more than double the average water consumption in Australian cities. A public consultation process began that resulted in the Alice Springs Water Resources Strategy 2005 (Northern Territory Government, 2007).

This established a fundamental principle for the use and management of this non-renewable source – “not more than 80% of the estimated aquifer storage can be depleted over a period of 320 years (ie. 25% of the maximum allowable drawdown is permitted every 100 years).” Estimates of potable aquifer storage and projected water supply demand indicate at least 100 years, and perhaps up to 400 years, before the aquifer is depleted. Demand management is central, with capping of town water supply abstraction and water use efficiency plans (Turner *et al* 2003) adopted. Additionally water from the wastewater treatment plant is further treated through a water recycling plant and recharged via soil aquifer treatment basins, to overcome sewage overflows to a natural wetland in winter, and as a by-product replenishes the aquifer remote from the well field, reducing the net rate of depletion. When augmentation is ultimately necessary groundwater at Ti Tree Basin, 150km north could potentially be tapped.

### 3.6 Economics of groundwater use and demand management

Firstly considering the costs and benefits of groundwater supply to a groundwater user, for example in irrigation, the costs are composed of the capital cost of the well amortised to annual volume and energy costs for pumping. The value of their water use is proportional to use when use is highly efficient, but with excessive irrigation there are diminishing marginal benefits (Fig 8). However the full cost of supply includes environmental costs not borne directly or immediately by the groundwater user, such as flow depletion in streams, ecosystem impacts, salinity increase, loss of income by other groundwater users who lose access to groundwater and higher pumping costs for other groundwater users, in addition to consideration of shortened useful life of the aquifer due to depletion. Hence while an individual groundwater user perceives no constraint on profligate use of water, there is a volume beyond which there is a decline in the utility of the aquifer for the community at large.

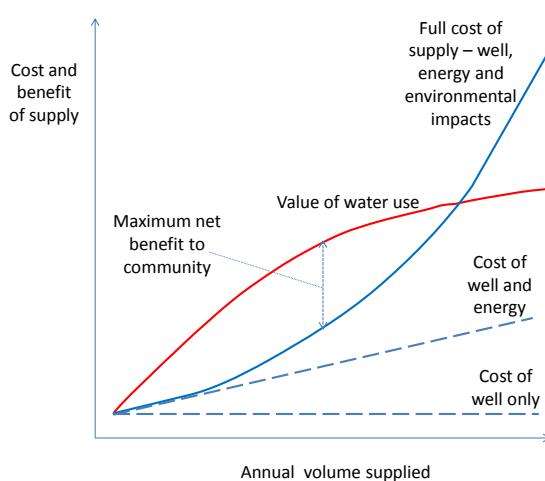


Figure 8. Costs and benefits of groundwater use in relation to volume of use as experienced by a single groundwater user and by their community and environment at large.

One corollary of this concept is a dry economic argument to suggest pricing of groundwater to constrain consumption. It is important to note that this is only one of a range of possible management interventions, and is illustrated in Figure 9. A price per unit volume is charged to the groundwater user to encourage efficiency of use and so that the utility function of the groundwater user is optimised at the same annual volumetric use that optimises the net benefits to the whole community. Just as there are environmental externalities associated with groundwater storage depletion, there are social and economic benefits of irrigation production that exceed the revenue stream to the groundwater user. These factors would need to be taken into account if implementing such a pricing system and account for the way in which revenue was used.

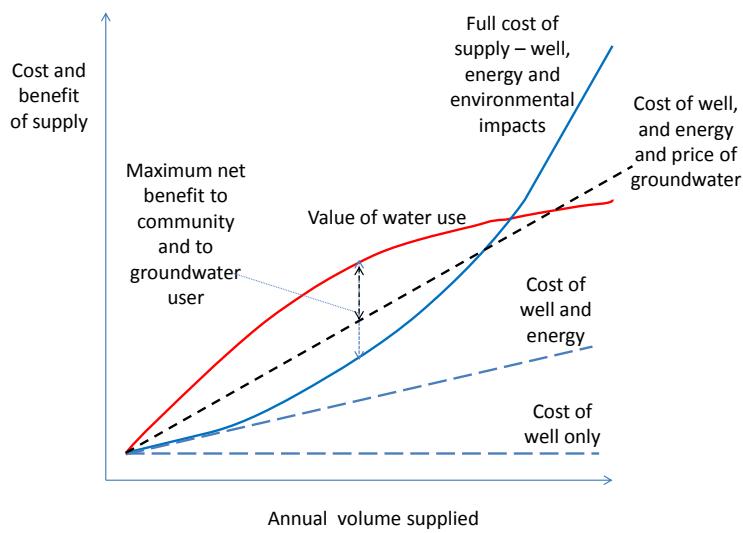


Figure 9. Costs and benefits of groundwater use in relation to volume of use as experienced by a single groundwater user including a price of water so that user and community utility are maximised by their community and environment at large.

### 3.7 Economics of incorporating managed aquifer recharge and alternative supplies

Managed aquifer recharge (MAR) can increase the value of water resources by transferring surface water in times of abundance to add to groundwater storage and thereby conserve water. This replenishes depleted groundwater and avoids evaporative losses, salinity increase and possibilities for blue green algal blooms if the water had been retained in surface reservoirs. The surface waters used for managed aquifer recharge may include natural waters from catchments, urban stormwater, water recycled from treated sewage effluent, desalinated water from brackish aquifers or the sea, and suitably treated industrial effluents. There is ample guidance on protecting human health and the environment for managing aquifer recharge operations (eg NRMMC, EPHC and NHMRC 2009, and Page *et al* 2010). However guidance on policies to account for MAR in water resources management is embryonic (eg Ward and Dillon 2011) and institutional arrangements are rare (a notable exception being the Arizona Water Bank). In semi-arid areas recharge is generally in the monsoon or wet season and recovery occurs in the dry season (Figure 10.) Aquifers that are already depleted make excellent storage targets because there can also be environmental benefits in replenishing such aquifers. However care is needed to ensure that groundwater replenishment is not at the expense of surface water ecosystems and water users downstream. Ideally there is an integrated surface water and groundwater allocation plan, accounting for their connectedness.

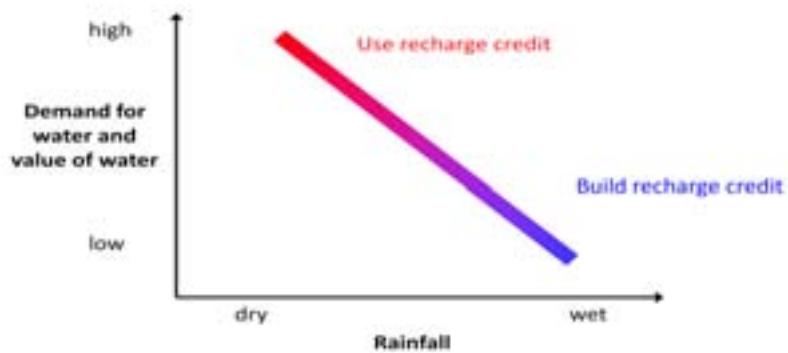


Figure 10 Managed aquifer recharge is a way of increasing the value of water resources by harvesting and storing water in the wet season for recovery during the dry season or as drought and emergency supplies.

A theoretical construct for prolonging the time to yield failure and for restoring currently over-exploited aquifers using a combination of demand management and recharge enhancement was presented by Dillon *et al* (2009b). See Appendix B. The full paper included case studies in Australia and India. However it did not address a determination of the most economic proportion of recharge enhancement and discharge reduction necessary to restore a depleting aquifer. That concept is introduced here.

For any aquifer, there will be a range of recharge options that can be ranked in order of increasing unit cost of supply. Similarly foregoing extraction for each use of groundwater will have a range of unit costs that can be ranked in increasing order. Each element of these lists has an associated volume and unit cost and the two lists may then be merged to identify the cheapest option and the volume of demand reduction or supply enhancement expected if that option were implemented (Figure 11). Depending on the degree of over-exploitation, a series of options may be required to achieve hydrologic equilibrium (as per Figure 4), or at least to extend the effective lifetime of the groundwater resource.

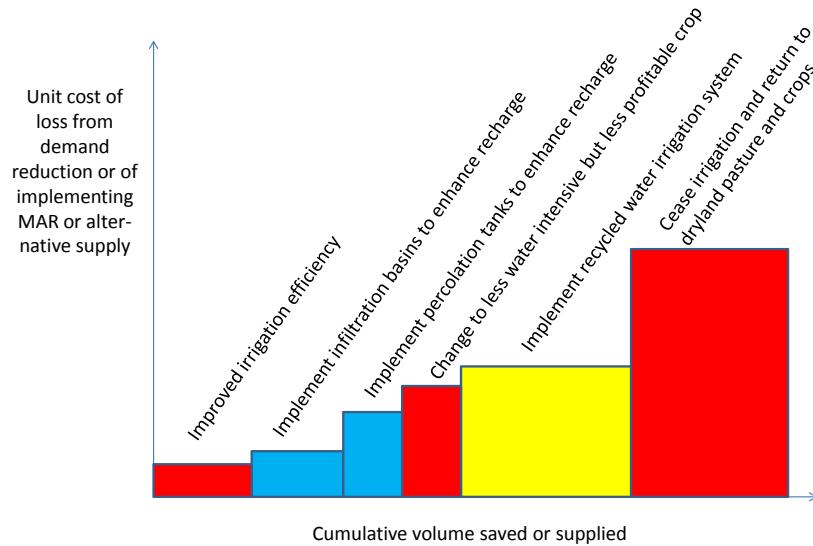


Figure 11 A logical combination of demand reduction (red), recharge enhancement (blue) and substitution of alternative supplies (yellow) may be made to reduce or eliminate groundwater depletion at least cost. Options and their relative costs and volumes are location-specific. However improved irrigation efficiency is often the least costly option and hence implemented first.

Figure 11 reveals plainly to groundwater users the choices to be made by stakeholders and the benefits of investing in recharge systems or alternative supplies in relation to the investments in improving irrigation efficiency, or the costs borne by changing crops or retiring irrigated fields to dryland systems. The decisions will depend on the relative costs of options and the capability of stakeholders to absorb costs. One way of covering costs for recharge systems could be to impose a unit volumetric charge for groundwater (as per Figure 9) which would also have the effect of encouraging irrigation efficiency. Implementing a charging system for groundwater is unlikely to elicit an enthusiastic response by groundwater users. However if they can see that their contribution to recharge facilities would be at a lower cost to them than the revenue otherwise foregone by reducing consumption by an equivalent volume, such a system would be easier to implement. This is how groundwater replenishment was able to commence in the Orange County Water Management District in California. The imposition, with community consultation, of a “groundwater replenishment assessment” funded the operations that reversed the salinisation of the over-exploited coastal aquifer. This has subsequently paved the way for larger replenishment systems using better quality water to improve the security, yield and quality of groundwater supplies (Mills 2002).

### **Box 13 Three pronged approach to managing groundwater storage in Arizona, USA**

Arizona, a State with declining groundwater levels, rapid urban population growth and vulnerability to drying water supply catchments, adopted its Groundwater Management Act in 1980 to curb groundwater overdraft (Megdal 2007). This was amended in 1986 to encourage recharge of groundwater with surface water in times of excess flows and recycled water derived from treated sewage effluent (Megdal 2007). Subsequently the Central Arizona Project (CAP) was completed, with a capacity to divert 1850 million m<sup>3</sup>/yr (20% of Arizona water use) from the Colorado River lifting it up to 730m and delivering via a 540km canal. This provides a substitute supply for irrigation and municipal use in three groundwater Active Management Areas (Phoenix, Pinal and Tucson AMAs). It is also a dominant source for groundwater recharge under the 1986 laws that allow banking of water to meet future needs and for drought relief (Megdal 2007). Recharge and recovery also serves as a mechanism for cities to use renewable Colorado River water indirectly rather than through construction of costly treatment plants (Megdal 2007).

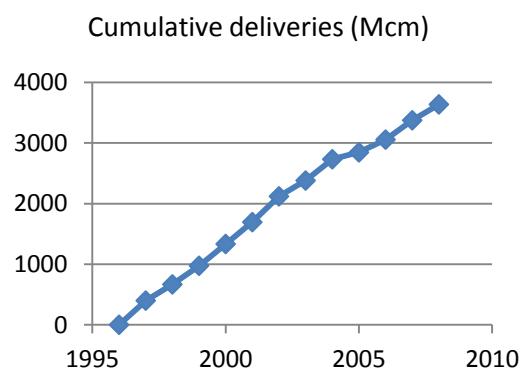
Arizona's innovation in groundwater recharge and the scale of its practice are possible due to extensive unconfined aquifers of high transmissivity, containing good quality drinking water supplies and overlain by permeable soils, as well as a highly developed system of permitting and reporting. These ensure that recharge is cost-effective and the benefits of water storage or banking are broadly dispersed and highly valued. A key component of Arizona's approach to water banking was the establishment in 1996 of the Arizona Water Banking Authority (AWBA). The AWBA was created to store water for multiple purposes; (1) storage for drought relief for CAP users; (2) support groundwater management goals of AMAs (3) support settlement of Indian water claims; and (4) bank Colorado River water separately to assist Nevada and California (Megdal 2007). AWBA invests funds derived from land taxes associated with the CAP, a levy on groundwater extraction in the Active Management Areas, and initially also from state appropriation. Investment in water banking by municipalities and urban developers in order to meet supplies for 100years for new developments also contributes to recharge, but is not coordinated by AWBA.

In the 14 years from inception to end of 2010, the AWBA had expended US\$272M to accrue 4,300Mm<sup>3</sup> of recharge credits at an average cost of 6.3 cents/m<sup>3</sup>. Of this volume 84% was for intrastate credits and 16% was banked on behalf of Nevada (from Arizona Water Banking Authority 2011).

Hence in Arizona, law that quantifies groundwater rights, water banking to increase groundwater storage and the CAP project substituting surface water for groundwater use, are the combined governance elements to reverse storage depletion. Further, in 2007 the Secretary of Interior signed a shortage sharing regulation and there is also work towards developing an agreed-upon groundwater recovery plan. Arizona's supply-side and demand-side regulations provide more degrees of freedom to address potential future reductions in surface water flows and ability to recharge, than demand-side management alone. Continued scenario planning is expected to give even more resilience in addressing water scarcity.



Agua Fria Recharge Project infiltration basins recharge CAP water to replenish groundwater and accumulate a recharge credit for future groundwater use. (from Arizona Water Banking Authority)



Cumulative water deliveries by Arizona Water Banking Authority 1997-2008 (Arizona Water Banking Authority 2011)

### 3.8 Further groundwater management questions and principles

#### *Why manage groundwater recharge/discharge or storage and which?*

For many years dates and coconuts were high valued products of groundwater irrigation on the coastal Battina Plain of Oman. The subsequent establishment of irrigated lucerne for goat fodder on the sandy plains inland was a very much larger use of water for a much lower valued product that could even be imported at lower cost. However due to the lucerne production, saline groundwater ingress occurred causing large areas of palm groves to die and the rest threatened. An industry was lost and land salinised because of inadequate understanding and management of groundwater. This is an example of where the value of effective management of groundwater could have amounted to the total ongoing value of production based on groundwater supplies.

Investment in groundwater management is a fundamental responsibility of government and one with high benefit to cost ratio, and with significant social value particularly where aquifers are stressed and competition among users is high.

#### *Who sets the objectives? Stakeholders or governments?*

While governments have the responsibility for management, setting the objectives and forming plans involves engagement with stakeholders to achieve success. Several models for engagement are in common use. **Catchment or aquifer management boards** may be empowered to make decisions or to make recommendations to a Minister of Water Resources who makes the final decision. Such boards commonly consist of stakeholder community representatives with some technical support from government departments.

In some cases Boards may be empowered to generate their own resources, for example by imposing a water resources management levy on groundwater users, land owners, or local government bodies within the catchment or groundwater system. These funds support monitoring, reporting, informing stakeholders, developing water management plans, and implementing them.

Other bodies such as **groundwater users associations** may be formed to support the interests of their members. These may suggest or even fund initiatives for recharge enhancement, alternative supplies or communally supported improvements in irrigation efficiency. In Spain water managers have developed a range of methods to establish participatory schemes for groundwater and environmental stewardship by water users.

Institutions such as **water banks** (Fig 12) can also be established by governments to establish the mix of water resources in use where demand is growing. These can identify the specific options for new supplies or water conservation (as in Fig 11) and the means of funding these to minimise costs of achieving government policy objectives in regards to water, agriculture, environment, and urban and land planning and development. An example is the Arizona Water Bank (Box 13), that makes investments in managed aquifer recharge to meet needs for a growing population in an arid area with an extensive and transmissive aquifer. This is a very lean operation staffed by only two to four people. That model may be extended to address all sources and uses of water in a region, and has potential to be a key institutional initiative for adaptation to climate change.

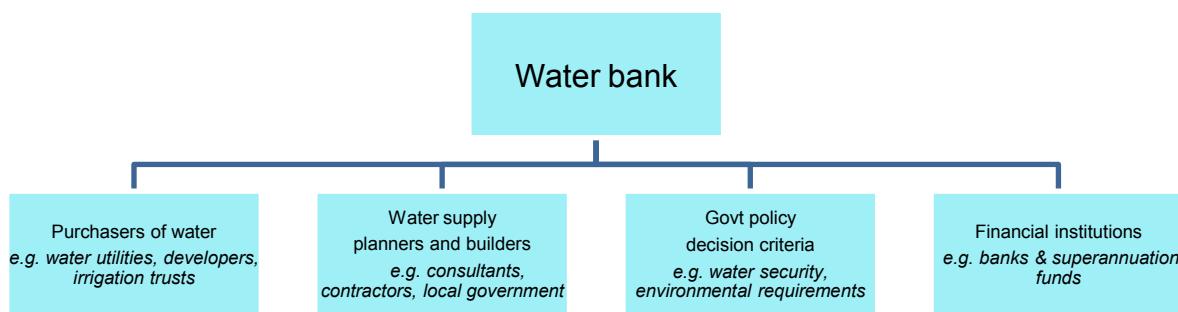


Figure 12 A water bank can provide a transparent approach to water resources development and allocation decision making. This unifies the demand and supply market for water over a region that is larger than that considered by single purchasers and suppliers and thereby can create efficiencies in costs, water utilisation and maximise resource utility while meeting social and environmental needs.

*Changing climate, population and land use and changing recharge and discharge expectations and process for revision of objectives*

No water allocation plan is expected to endure indefinitely. Changes in magnitude and spatial and seasonal patterns of demand, variations in expected recharge rate and changing social considerations of the trade-off between level of economic production and environmental consequences need to be accommodated. Improved knowledge over time of the status of groundwater and surface water resources and their dependent ecosystems will also affect the level of allocation which would be adjusted periodically(as per Figure 3). In semi-arid systems of southern Australia with slowly changing groundwater storages allocations are typically required by law to be re-evaluated each five years with public consultation on allocation plans prior to adoption and implementation. This periodic revision of allocation plans, also allows consideration of supply side measures such as managed aquifer recharge and alternative supplies.

*Managing falling and rising trends*

Generally, the value of groundwater use depends on the *volume and timing* of that use. The environmental impacts generally relate to change in the *level* of the water table where this was initially in close proximity to the ground surface or beneath stream channels, lakes, or the sea. The costs and greenhouse gas emissions of groundwater extraction depend on groundwater levels in the vicinity of pumping wells. This is also the area most prone to land subsidence where porous media are compressible. Hence the benefits of consumption relate to volumes and the costs relate to levels.

Where unconfined aquifers have a deep watertable prior to development or are distant from receiving streams the immediate environmental costs are likely to be least. Aquifers with high effective porosity are more likely to yield more benefit per unit of environmental cost. However aquifers that contain qanats (groundwater falaj), or intermittently hydraulically connected ephemeral streams, or only shallowly incised receiving streams, are highly vulnerable to small changes in groundwater levels adjacent these features. In these circumstances the proximity of groundwater extraction is as important as the volume. These discharge zones need to be considered carefully when allocating groundwater entitlements, and exclusion zones may be specified (eg in UAE near falajs). Surface water bodies are also potential sources of water for groundwater replenishment, subject to surface water

allocation plans, however the counter-cyclic timing of recharge and demand, and the importance of flow in dry periods, requires quite sophisticated management approaches. A simpler alternative, where available, is to replace groundwater allocations with alternative supplies in these more sensitive areas.

Groundwater management is also needed where groundwater levels are rising due to change in land use (such as large scale removal of deep rooted vegetation), climate change or importing water supplies that result in drainage of excess water to a water table. This can result in restrictions on land use change, developing conjunctive use of groundwater and surface water to offset rising levels, and introducing pricing systems to encourage balance of use from sources that allows hydraulic equilibrium to be established in the aquifer in an acceptable depth range. As a last resort groundwater drains may be used, taking account of the impacts on surface water systems down-gradient.

#### *Transitional arrangements for sustaining resources*

For groundwater managers facing legacy deficits and an inadequate legislative framework, transitional strategies are needed. Many jurisdictions are a long way from an aquifer-friendly entitlement system, either for groundwater use or for managed aquifer recharge credits. . However most have in place permit-based systems to allow use or recharge. Further information may be needed to enable consumptive pool entitlements to be well-defined and to define sharing arrangements. A transitional pathway is needed to progress towards intended governance arrangements that optimise the value of the water resource (Fig 13).

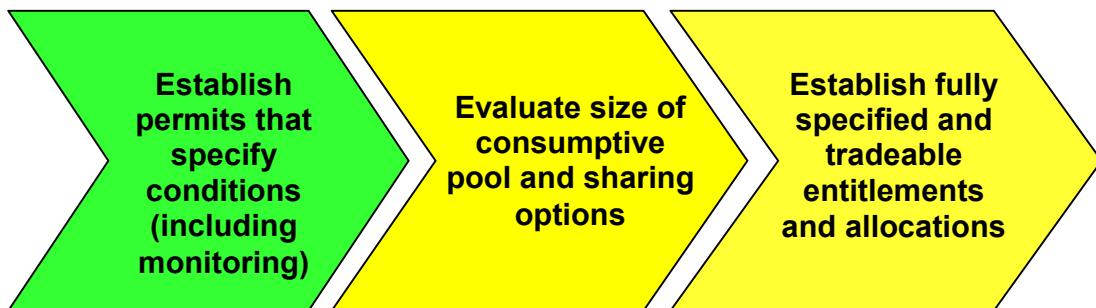


Figure 13 Pathway for policy implementation from regulation to entitlements

#### *Metrics for monitoring and management*

Monitoring the progress towards the intended objectives of groundwater management provides the only defensible assessment of the effectiveness of management. Clear criteria are needed that relate to economic productivity, environmental and social factors. Productivity in irrigation areas is usually recorded by Departments of Agriculture who survey farmers, and evaluate yields and prices. Water use is a useful measure where resources allow as this gives clear feedback to irrigators on their water use efficiency. It would normally be expected for all public water supplies to record volume extracted as well as monitor its quality. Groundwater levels in environmentally sensitive areas, and in the drawdown cone of centres where wells are dense, are valuable. More sophisticated measures include the area where piezometric surface is above sea level ( or some other defined level) at the end of the irrigation season, or estimated recoverable storage volume based on a network of piezometers. Social indicators may include the number of groundwater users who have improved irrigation methods, the number of investors in

managed aquifer recharge projects, time required for irrigation management. More comprehensive lists are given by Beernaerts (2006).

#### *Integrated water resources management of quantity and quality*

For historical reasons, the management of water allocations has largely been undertaken by natural resources management authorities and management of water quality by environmental protection and health authorities (Fig 14). Because quantity and quality are interdependent this often leads to harmony between authorities on policies, but on some occasions can lead to conflicting objectives. Managed aquifer recharge with water of slightly poorer quality than the native groundwater but of much better quality than groundwater degraded by saline intrusion, is an example, where the NRM department is in favour but the environment protection authority is not. A holistic view is required with an understanding of the consequences of the alternative management scenarios for both quantity and quality in order to find a path that optimises the utility of the aquifer while meeting public health and environmental constraints. An aquifer that provides unrestricted irrigation but no drinking water supply may be a sub-optimal strategy when costs of alternative supplies are taken into account.

Attribute Instrument	Quantity NRM policies	Quality Water quality management guidelines NRMMC-EPHC-NHMRC 2009a
Management Issue  Resource	Water and Storage Entitlements and Allocation	Human Health and Environment Protection
Surface water	<ul style="list-style-type: none"> <li>Environmental flow requirements (including urban stormwater and sewage effluent)</li> <li>Water allocation plans and surface water entitlements</li> <li>Inter-jurisdictional agreements</li> </ul>	<ul style="list-style-type: none"> <li>Catchment pollution control plan</li> <li>Water quality requirements for intended uses of recovered water</li> <li>Risk management plan for water quality assurance</li> </ul>
Groundwater	<ul style="list-style-type: none"> <li>Resource assessment accounting for groundwater-dependent ecosystems</li> <li>Groundwater allocation plan and groundwater entitlements</li> <li>Demand management</li> <li>Allocatable capacity and entitlement for additional storage in the aquifer</li> <li>Transfer of entitlements among groundwater users and from MAR operations</li> <li>Inter-jurisdictional agreements</li> </ul>	<ul style="list-style-type: none"> <li>Groundwater quality protection plan</li> <li>Account for recharged aquifer in accordance with MAR guidelines</li> <li>Water quality requirements for intended uses of groundwater</li> <li>Risk management plan for water quality assurance beyond attenuation zone, accounting for aquifer biogeochemical processes</li> </ul>

Figure 14. Integrated natural resource management and health and environment issues to be addressed for effective governance of surface water and groundwater resources involving managed aquifer recharge (adapted from Dillon *et al* 2009a)

### *National government role in setting water resources management policies and principles*

In many countries there are a hierarchy of government policies at national, state, catchment and local level, with national government taking responsibility for establishing governance principles, investing in water management initiatives and ensuring coordination of policies across state jurisdictions which generally have statutory responsibility for water management. Within catchments and groundwater systems, these policies are enacted including monitoring and evaluation of the resource, with devolved state technical support for informing and consulting with stakeholders and in establishing and maintaining accounting systems for entitlements and allocations. At local or village level action in implementing on-ground practices and infrastructure, enacts change in accordance with policies set at higher levels combined with local innovation and adaptation.

Many examples of highly effective local interventions to restore groundwater storage and resilience, reported earlier, have been initiated at local level. They have not relied on supportive national water resources policies, although the presence of such policies would greatly expand such initiatives. However rural employment and agricultural extension services at national and state levels have facilitated change. For example the Mahatma Ghandi National Rural Employment Guarantee Act (2005) has invested more than 50% of up to US\$B8/year on water conservation, harvesting and groundwater replenishment works.

In the inaugural Indian Water Week, in April 2012, the Government of India (2012a) released for public comment a Draft National Water Policy. Revised in June 2012, this presents a comprehensive approach to integrated water management surface and groundwater, quantity and quality) with objectives of equity, social justice and sustainability (Box 14). It declares that whereas groundwater is currently “*still perceived as an individual property and exploited inequitably and unsustainably in places*”, that water needs to be “*managed as a community resource, held by the state under public trust doctrine to achieve food security, livelihood, and equitable and sustainable development for all.*” If this draft policy is implemented and used it to help frame activities supported by NREGA and other government programs, it would have the largest international impact on reducing the groundwater imbalance quantified earlier.

#### *Box 14. Contents of Indian Draft National Water Policy*

**Govt. of India  
Ministry of Water Resources  
DRAFT NATIONAL WATER POLICY (2012)**

1. Preamble
2. Water framework law
3. Uses of water
4. Adaption to climate change
5. Enhancing water available for use
6. Demand management and water use efficiency
7. Water pricing
8. Conservation of river corridors, water bodies and infrastructure
9. Project planning and implementation
10. Management of flood & drought
11. Water supply and sanitation
12. Institutional arrangements
13. Trans-boundary rivers
14. Database & information system
15. Research & training needs
16. Implementation of National Water Policy

## 4. Prospects for slowing or reversing trends through improved governance

### 4.1 Conclusions from case studies

The case studies presented in boxes in the previous section reveal there is considerable scope for securing social, economic and environmental benefits through selection and adoption of governance methods relevant to the situation and to the affected community. Table 2 summarises the key questions concerning the state of the aquifer before the intervention, the capability of the community for collective action (which in most cases was revealed as part of the process of engaging with the community), and whether alternative water supplies were available. These answers determined the suitability of the three categories of groundwater governance, which are colour coded in Table 2 to match Figures 4 and 11.

Table 2. Concise summary of case study attributes, management instruments employed and effectiveness

Case study	was g/w over-allocated?	Existing social capability for collective action?	Sufficient other water resources available ?	Demand management	Managed aquifer recharge	Alternative supplies	Effectiveness#
Ilocos Norte, Philippines	no	yes	localised	farmer led			yes
Andhra Pradesh, India	yes	Yes now	ephemeral streams	farmer led	localised		yes
Maharashtra, India	yes	yes	ephemeral streams	ban on tube wells and sugar cane	strategic		yes
Castilla y Leon, Spain	yes	no	river and treated wastewater	user collective failed to curb use	basins	treated wastewater	no
Namoi Valley, Australia	yes	yes	Namoi River	Entitlements issued		river water (also licensed)	yes
Kitui, Kenya	yes or not available	yes	ephemeral streams		sand dams		yes
Coastal Bangladesh	Water too brackish	yes	rainwater and pondwater		recharge wells		yet to be assessed
Mancha Occidental, Spain	yes, heads fallen 80m	unknown	Canal del Guadiana		recharge wells	Guadiana channel	yet to be assessed
Bangkok, Thailand	Yes- heads fallen 60m, land subsidence	not relied on. Diverse and dispersed g/w users,	treated surface water	Pricing to curb demand		treated surface water	yes
Alice Springs, Australia	yes – heads fallen 50m	Government is dominant user	treated wastewater	Entitlements and use efficiency measures	minor soil aquifer treatment		yes for adopted objective
Arizona, USA	yes	yes	CAP and treated wastewater	Groundwater rights assigned	water banking	CAP and treated wastewater	yes

# storage objectives (and water quality objectives where known) are met and management process is accepted by groundwater users

Blank cells indicate that the particular governance instrument was not applied in that situation

The right hand column of Table 2 is an interpretation of the effectiveness of the governance arrangements based on the reporting of these interventions. That is, if groundwater storage increased where it had previously been depleted management was considered effective. In one case, coastal Bangladesh, the replenishment was intended to establish fresh groundwater in a previously unusable brackish aquifer. Although results are too early to judge success at this site, that method has been used effectively in Australia for the same purpose (eg Dillon *et al* 2009a).

Single strategy interventions were used in only three of these cases and each of them was for groundwater systems that either were initially in hydrologic equilibrium ( Ilocos Norte, Philippines), or water was brackish (Bangladesh) or there was a low rate of use or no use because the scale of the resource was small (Kitui, Kenya). In each case there was a high degree of cooperation inherent in the community so there was confidence that new resources would be managed for the equitable benefit of the community.

In five cases there was one demand side measure and one supply side measure used together. In Maharashtra, Andhra Pradesh and Alice Springs cases managed aquifer recharge is being used selectively for groundwater replenishment, and in Bangkok and Namoi Valley alternative surface water supplies are used to replace groundwater use and restore groundwater equilibrium.

In two cases, supply side management alone is applied and in the older of these two cases, groundwater levels are continuing to fall because the increase in supply has been met by a corresponding increase in demand.

The final case, in Arizona, contains the three management interventions used concurrently and is providing a robust means of managing groundwater resources in an area with significant population growth and a dry and drying climate.

In all successful cases, consultation with the community was important, so stakeholders could understand the nature of the problem, the options for dealing with it and contribute selecting and shaping the options in line with resources available. The table shows that unless the community is small and cohesive, concentrating on effective demand management is essential and should precede supply side options. Supply side options may be used as inducement to participate in demand management, recognising that in some circumstances it may be more economic to cover supply costs to maintain production than to rationalise production, as illustrated in Figure 11.

A current limitation for managed aquifer recharge as a groundwater management strategy is the lack of experience of most water resources agencies with its use. Siting, design, operation, maintenance and water quality protection are topics that need to be understood, so that investment in managed aquifer recharge projects provides consistent ongoing success. There is an uneven spread of knowledge and competence in implementation and maintenance of projects, particularly in developing countries, where it can be highly competitive for enhancing, sustaining and improving water quality of town and city drinking water supplies as well as agricultural supplies. To address this knowledge gap IAH Commission on Managed Aquifer Recharge and UNESCO are establishing a MAR-NET network of centres of national concentration of expertise in managed aquifer recharge with associated demonstration projects to provide training in this aspect of groundwater management which seriously lags our competencies to extract water from aquifers. The network will lead to efficient exchange of information, teaching resources and facilitate expertise from a range of disciplines to be brought to bear. Meetings would be useful between the ISMAR series of conferences, the next of which will be in Beijing 15-19 Oct 2013 [www.ismar8.org](http://www.ismar8.org)

## 4.2 Scope and potential for managing and improving groundwater storage and recovery

It is evident that groundwater policy reform is required and that entitlement to groundwater through land ownership or prior right does not work and cannot work in slowing or reversing groundwater depletion. These methods have conspicuously failed to allow volumetric allocations to be modified equitably as the environmentally protective allocatable resource pool becomes better defined. Furthermore, they oppose maximisation of the utility of the groundwater resource. Like the monkey unable to retrieve its hand from the jar without releasing the fruit, unless these systems are abandoned there is no hope of an acceptable outcome.

Improving irrigation efficiency and agronomic methods can reduce water use while sustaining or enhancing production. This should be considered in every portfolio of groundwater management policies. Improved awareness of the magnitude and degree of resilience of the groundwater resources will help communities understand that the resource is finite, shared and there are severe consequences to all groundwater users and to connected streams and ecosystems if too much groundwater is extracted.

The key issue is for all groundwater users to understand they are sharing a common good, and that there is a finite limit to the total that can be shared. Two distinct and quite separate processes are required;

- (1) a scientific assessment of the magnitude of the allocatable resource, repeated periodically, based on credible monitoring of the groundwater storage and water use
- (2) a socially acceptable way for shares (entitlements) in that allocatable resource to be allocated to groundwater users, taking account of social, environmental and economic factors.

Allocations are made for a period based on multiplying the currently determined allocatable resource by the share of each groundwater user. Shares and allocations should be transferable, and should be registered as a property right, and traded in an open market subject to rules to protect the environment and other groundwater users.

Legislation may be required to vest the groundwater resource in the ownership of the State. Groundwater users recognise they have only an ambit claim to a continued right to the volume of groundwater previously attached to land ownership, as that volume will not be available unless total demand on the system was to reduce. However these users are taken into account in assigning shares of the allocatable resource.

In the event that there is disagreement among users, historical uses only should be taken into account, the shares of an individual should be based on the ratio of their historical use to the sum of historical uses of all individuals over a period concluding before share apportionment is calculated. Intended new users of groundwater would need to buy their allocation from a willing seller on the market at the price they agree.

Demand management is a key element for sustaining groundwater supplies, and where other water resources are available, this can be assisted by managed aquifer recharge and supply augmentation. These additional measures can be applied most effectively where there is an entitlement system for groundwater use. For example new or existing groundwater users may be able to pay for managed aquifer recharge systems through the sale of some of the allocations that MAR may yield. Similarly, if supply augmentation with surface water systems occur, entitlement to access this water may require foregoing groundwater entitlements so as to ensure there is a benefit to the aquifer (as was required in Bangkok).

There are potentially significant benefits in incorporating managed aquifer recharge and/or supply augmentation where the costs of these options in monetary units per volume of water are less than the equivalent cost of reducing production. There may be additional benefits where otherwise wasted water from urban areas or industries is harvested and treated to make it compatible with the aquifer and the existing uses of groundwater. Development of expertise is needed to capture these opportunities.

A framework for incorporating managed aquifer recharge into water resources management policies is presented by Ward and Dillon (2011) (Table 3). It consists very simply of applying the three instruments; entitlements, allocations and use conditions to each of the four key elements of managed aquifer recharge; access to recharge water, recharge, recovery and end use. It includes a recommended practical procedure, including constraints, on trading of recovery credits. This may be used to facilitate groundwater users associations, and provide a way of sourcing investment in managed aquifer recharge by beneficiaries across the groundwater basin.

Table 3. Natural resource management for MAR based on the robust separation of rights (from Ward and Dillon, 2011)

MAR governance instrument:	Source Water Harvesting	Recharge	Recovery	End Use
Entitlement	Unit share in surface water, stormwater or effluent consumptive pool, (i.e. excess to environmental flows)	Unit share of aquifer's finite additional storage capacity	(Tradeable) extraction share which is a function of managed recharge.	N/A
Periodic allocation	Periodic (usually annual) allocation rules. Potential for additional stormwater or treated effluent subject to high flows or development offsets	Annual right to raise the water table or piezometric head subject to natural recharge and total abstraction	Extraction volume contingent on ambient conditions, natural recharge and spatial constraints	N/A
Obligations and condition	3rd party rights of access to infrastructure for stormwater and sewage	Requirement not to interfere with entitlements of other water users and water bankers	Existing licence may need to be converted to compatible entitlement to extract (unit share)	Water use licence subject to regional obligations and conditions, for use and disposal

N/A = not applicable

The entitlement to recover a volume of water that relates to water that has been recharged to an aquifer water in general should be tradeable, but with constraints on trading entitlements into drawdown cones or trading into parts of aquifers that are fresher than the water being recharged. A set of entitlement descriptions is given in Table 4 based on the hydraulic retention time of the aquifer and whether the aquifer is already over-allocated. Further information is found in Ward and Dillon (2011, 2012).

Table 4 Recovery entitlement descriptions for different aquifer characteristics (from Ward and Dillon 2011)

	Over-exploited aquifer		Aquifer in equilibrium	
	Long hydraulic retention time T <sup>a</sup>	Short hydraulic retention time T	Long hydraulic retention time T	Short hydraulic retention time T
	T>30 years	T<30 years	T>30 years	T<30 years
Maximum cumulative % recovered *	90% (S)	90% (S)	100% (S)**	100% (S)**
Time period for recovery (years)	30	T	30	T
Depletion rate for stored water (%) *	0 (S)	100/T (S)	0 (S)	100/T (S)
Maximum recovery in any year	<max annual recharge	<max annual recharge	-	-
Transfers permitted	yes	yes	yes	yes

<sup>a</sup> T represents the hydraulic retention time of recharged water

\* maximum percent recovered in a brackish aquifer is constrained by the salinity (S) of the recovered water needing to meet the requirements for its use. Recovery ceases when water reaches this salinity threshold or the percentage constraint whichever occurs first.

\*\* in some brackish aquifers the salinity constraint may not be reached until recovery significantly exceeds 100% recharge. In such cases the MAR operator could apply for entitlement to native groundwater for the amount in excess of their recovery credit (100% recharge volume).

#### 4.3 A unifying synthesis

Principles and high level frameworks for groundwater management approaches have been presented with emphasis on community based management (Wegerich 2005) and integrated water resources management (Forster and Ait-Kadi 2012). In harmony with these but at a lower level, a unifying synthesis of groundwater management success reported in this thematic paper is illustrated diagrammatically in Figure 15. This illustrates pathways through policy reform that have been shown to be successful in achieving agreed objectives for unstressed and stressed aquifers. This takes account of stakeholders capabilities for collective action and the prospects for managed aquifer recharge or water supply augmentation in concert with demand management where alternative water resources are available.

While a number of case studies have been highly successful in achieving objectives that account for economic, social and environmental objectives, few case studies have embraced a holistic governance arrangement that enable synergistic effects of managing recharge and discharge in concert. The strategy, together with stepwise pathway is intended to serve as a basis for designing national investment programmes related to groundwater equilibrium management.

Cost sharing between government and groundwater users may be used as a lever to implement reform. Where this is possible, government investment may depend on groundwater users contributions to efficiency measures and reduced use, alternative supplies, managed aquifer recharge and other groundwater management costs. Users share of costs would be in proportion to their share of entitlements to the allocatable resource.

If groundwater users are unable to make a contribution, this may in some circumstances suggest that the value of their crops grown with groundwater are low. A virtual water perspective on the efficiency of growing those crops in wetter areas, even outside the country, may show that there is higher value to be obtained by switching to other crops or not irrigating to prolong or sustain the availability of water to support crops with higher value per cubic metre of water used. A cap and trade system will allow transfer of cash from water buyers with high valued crops to those exiting irrigation farming of crops with low value per cubic meter of water used. In some cases, the return on sale of water allocation would exceed the net revenue for growing a crop, and would assist in establishing new low water-use enterprise or relocation.

Fig 15 illustrates a pathway forward for a range of circumstances, to prevent over-allocation where aquifers are able to supply existing irrigation and other water supply demands without environmental or ecosystem degradation. It also aims to develop capability for collective management where it does not already exist so that communities are informed and empowered. Where over-allocation already occurs, there needs to be an assessment of whether other sources of water are available, allocatable and economic, for managed aquifer recharge or to substitute for groundwater use. These may include surface water from catchments, even if only intermittently in excess of environmental flow requirements, and treated urban runoff and sewage, backed by water quality management with water safety plans enacted, including monitoring and treatment. Combinations of demand reduction, managed aquifer recharge and alternative supplies may then be identified, prioritised and sequentially implemented. Normally improving irrigation efficiency will the highest priority activity. In the absence of alternative supplies, demand reduction measures, combined with periodic assessment of the prospective lifetime of the resource will allow planning for transition from agriculture to low-water use livelihoods, including industrial and commercial enterprises. To compensate food production would need to be enhanced in other locations where water is more plentiful.

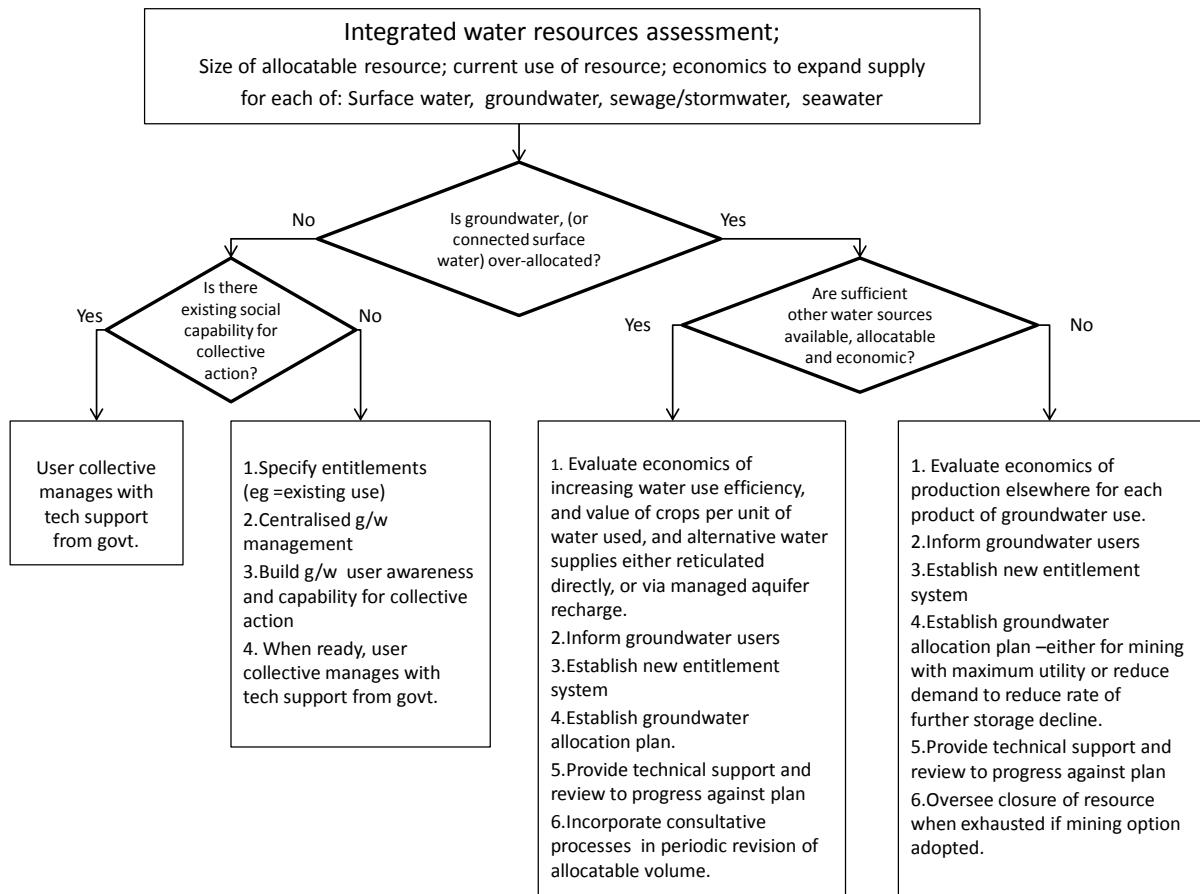


Figure 15 A decision tree to illustrate pathways through policy reform that have been successful in achieving agreed objectives in stressed and unstressed aquifers

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## **Appendix A: Generic Terms of Reference**

### **Thematic Paper 4: Management of recharge/discharge processes and aquifer equilibrium states.**

#### **Background**

These Terms of Reference (ToR) arise from the GEF Groundwater Governance Project (see Project Document GCP/GLO/277/GFF) and concern the preparation of a series of Thematic reports that are to be prepared as part of Component 1 of the project. The Component 1 is aimed at the compilation of the global state of groundwater governance in relation to groundwater supply and demand (quantity and quality); the outcome of this Component is stated as

“Broad agreement on the scientific and economic issues in relation to groundwater management and a consensus on the scope for future action; and enhanced cooperation and synergies among UN Water Agencies, major IFIs and key NGOs professional associations and client countries.”

Several Thematic Papers are to be prepared and In broad terms these papers will synthesize present knowledge and experience on key economic, policy, institutional, environmental and technical aspects of groundwater management together with emerging issues and innovative approaches.

The Thematic Papers are related to several detailed case studies whose terms of reference (see Annex 6 of prodoc) should also be referred to. The current Thematic Paper ToR concerns;

Management of recharge/discharge processes and aquifer equilibrium states;

Other Thematic Papers also being prepared concurrently with this one include:

The tendencies in groundwater pollution; trends in loss of groundwater quality and related loss of aquifer services (inc. ecosystem response); Conjunctive use and management of groundwater and surface water within existing irrigation commands and public supply sources;

Urban-rural tensions and opportunities for co-management

#### **Overall Purpose**

The purpose of these GEF Project Thematic Papers is to take stock of the state of groundwater management and governance in their specific physical, institutional or social „domains”. The Papers will diagnose the thematic issues and examine the prospects for regaining aquifer integrity and function or mitigating further impacts through improved governance. In this way, the Papers should demonstrate where global benefits (in terms of aquifer integrity and function) can accrue. The Thematic Papers will supplement the detailed case studies with relevant examples. Once complete the Thematic Paper will be used to compile a Synthesis Document which will be used for informing the regional consultations in Component 2 of the project.

This Thematic paper covers management of recharge-discharge processes & aquifer equilibrium and it will provide a macro view of the conditions under which the recharge-discharge is managed in various domains. The diagnosis will encompass linkages between the various domains and the prospects for halting or retarding the onset of declines and loss of the state of equilibrium.

#### **Approach of thematic paper**

The paper should attempt to present a clear account of the effectiveness of groundwater governance or the impact of its absence in relation to the management of recharge and the discharge of water from aquifers

ToRs for Thematic Papers to be prepared by IAH Experts

A working definition of „governance” in relation to water can be taken as.

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

It is anticipated that a project meeting (scheduled for end April 2011) will further define the scope of governance in relation to groundwater.

#### **Suggested structure**

##### **Thematic Paper 2: Conjunctive use and management of groundwater and surface water**

1. Introduction (1 page)

##### Part 1: Baseline

2. Concepts and mis-conceptions of conjunctive use (3 pages)
  - The water resource in aquifers vs. the water resource in surface systems

- The paradigm of “integrated resource management” and conjunctive resource management
  - Aquifers as the „free subsurface space” that may complement demand from surface systems
3. Typologies of aquifers involved in conjunctive use & management (3 pages)
    - Systems that occur naturally that are used spontaneously
    - Systems that are engineered and used in a planned scheme
    - The drivers that promote or deter productive conjunctive use
    - Institutional barriers to wider adoption of conjunctive use (where opportunities exist)
  4. Existing governance arrangements for conjunctive use (socio economic, legal and institutional analysis (5 pages)
    - schemes promoted by public agencies (water supply, waste disposal , irrigation)
    - autonomous adaptation - schemes promoted by users directly

Part 2: Diagnostic

5. Assessment of successes and failures of conjunctive use (3 pages)
  - Successful schemes & their key features
  - Failed schemes and key lessons learnt
  - Potential schemes that may be viable but have never been assessed for their feasibility
  - Recipe for success: typology of the aquifer – river system and the profile of user organisation
6. Scope for securing social and environmental benefits through implementing a conjunctive use scheme (4 pages)
  - Social benefits in terms of cost, increased (agricultural) productivity, poverty alleviation, etc
  - Environmental benefit in terms of sustaining the aquatic eco systems and/ or productive landscapes
  - Benefits accruing from building resilience to climatic factors, especially from increase in variability
  - Long term economic benefits from avoided future costs arising from loss of reservoir yields
7. Moving from use to management - a package of governance tools improve use and promote the adoption of conjunctive use (2 pages)
  - Scope and type of institutional strengthening and capacity development
  - Legal and economic instruments

Part 3: Prospects

8. Projecting the potential demand for schemes that use conjunctive use (2 pages)
9. Prospects for promoting the approach through economic instruments (3 pages)
  - direct measure
  - indirect measures
10. Prospects for breaking through the institutional barriers (3 pages)
11. Doing real IWRM - making conjunctive use the default setting (2 pages)
12. Conclusions (1 page)

## Appendix B: Combined effectiveness of demand management and managed aquifer recharge to address aquifer depletion (extract from Dillon et al 2009b)

The likely effectiveness of managed aquifer recharge to address groundwater over-exploitation may be determined approximately by conceptualising the irrigation demand and aquifer properties and levels as uniform and with the same spatial extent. Assuming that the storage ( $S$ ) accessible to irrigation wells in the aquifer is homogenised over the irrigation area, then if extractive discharge ( $D$ ) expressed as mm/year exceeds the rate of recharge  $R_n$  (natural recharge plus deep seepage), then the average number of years ( $T$ ) before yield failure occurs will be given by:

$$T = S / (D - R_n) \quad (1)$$

If managed aquifer recharge is expressed as an effective rate  $R_m$  over the irrigation area, and groundwater discharge management methods reduce discharge by  $D_m$  then the intent is to attain an equilibrium (where  $T_m \leq 0$ ). However, less effective efforts serve to prolong the average number of years ( $T_m > 0$ ) before yield failure occurs as given by equation (2):

$$T_m = S / ((D - D_m) - (R_n + R_m)) \quad (2)$$

where  $D$  = discharge (pumping for drinking, irrigation, industry) (mm/year);  $D_m$  = reduction in discharge due to demand management (increased irrigation efficiency, substitution of surface supplies or restrictions on groundwater use) (mm/year);  $R_n$  = natural rate of recharge and including irrigation deep seepage (mm/year);  $R_m$  = effective rate of managed aquifer recharge (mm/year);  $S$  = storage accessible before yield failure (mm) = accessible saturated thickness\* porosity;  $T$  = years until yield failure if  $D > R_n$  (no failure otherwise as not over-allocated); and  $T_m$  = years until yield failure if  $(D - D_m) > (R_n + R_m)$  (no failure otherwise as management is effective in sustaining yield.)

The prolonging of irrigation in an over-allocated aquifer by managing aquifer recharge and discharge is therefore given by:

$$T_m / T = 1 / (1 - (R_m + D_m) / (D - R_n)) = 1 / (1 - r - d) \text{ for } r + d < 1 \quad (3)$$

where  $(D - R_n)$  = annual deficit = rate of over-exploitation;  $r = R_m / (D - R_n)$  = proportion of deficit addressed by recharge enhancement; and  $d = D_m / (D - R_n)$  = proportion of deficit addressed by discharge reduction.

Hence there are three management scenarios for restoring an over-allocated aquifer to hydrological equilibrium:

- (1) where managed aquifer recharge alone is able to overcome the deficit, (i.e.  $r \geq 1$ );
- (2) where demand reduction alone is sufficient to restore hydrologic equilibrium (i.e.  $d \geq 1$ ), and
- (3) where the combination of managing aquifer recharge and discharge is able to restore hydrological equilibrium (i.e.  $r + d \geq 1$ ).

Consider a simple worked example of an aquifer 20-m thick with an effective porosity of 0.1 giving an accessible storage,  $S$  of 20 000 mm. If the excess of demand over natural recharge replenishment ( $D - R_n$ ) is 100 mm/year then from equation (1) the expected irrigation lifetime of the aquifer ( $T$ ) is 20 years. To sustain the system either 100 mm of recharge enhancement, 100 mm of discharge reduction, or a combination of recharge enhancement and recharge reduction totalling 100 mm is required. The extent to which irrigated production could be prolonged by combinations of recharge enhancement and discharge management for this example are shown in Table 1.

**Table B.1** Effectiveness of MAR in combination with demand reduction in over-exploited aquifer example expressed as years to yield failure,  $T_m$ .

$r = R_m / (D - R_n)$	$d = D_m / (D - R_n)$					
	0	0.1	0.2	0.5	0.8	1
0	20	22	25	40	100	$\infty$
0.1	22	25	29	50	200	$\infty$
0.2	25	29	33	67	$\infty$	$\infty$
0.5	40	50	67	$\infty$	$\infty$	$\infty$
0.8	100	200	$\infty$	$\infty$	$\infty$	$\infty$
1	$\infty$	$\infty$	$\infty$	$\infty$	$\infty$	$\infty$

## Appendix C Characteristics of aquifers and their influence on potential for managed aquifer recharge (adapted from Dillon and Jimenez 2008).

Characteristic	Feature and influence on managed aquifer recharge	
<b>Permeability</b>	<b>Moderate to high</b> <ul style="list-style-type: none"> <li>• High rates of recharge possible</li> <li>• Recharged water can be dispersed</li> <li>• Lower capital and energy costs per unit of water recovered</li> </ul>	<b>Low to moderate</b> <ul style="list-style-type: none"> <li>• Lower rates of recharge possible</li> <li>• Recharged water more localised</li> <li>• Greater capital and energy costs per unit of water recovered</li> </ul>
<b>Confinement</b>	<b>Unconfined</b> <ul style="list-style-type: none"> <li>• Surface infiltration methods viable</li> <li>• Unprotected from surface contamination</li> <li>• Storage capacity depends on depth to watertable</li> </ul>	<b>Confined</b> <ul style="list-style-type: none"> <li>• Well injection methods only</li> <li>• Protected from surface contamination</li> <li>• Storage capacity depends on aquifer thickness</li> </ul>
<b>Thickness</b>	<b>Thick</b> <ul style="list-style-type: none"> <li>• High storage potential</li> <li>• More sensitive to salinity stratification if native groundwater is brackish</li> </ul>	<b>Thin</b> <ul style="list-style-type: none"> <li>• Low storage potential</li> <li>• May limit rate of recovery by wells</li> </ul>
<b>Uniformity of hydraulic properties</b>	<b>Homogeneous</b> <ul style="list-style-type: none"> <li>• Minimal mixing and higher recovery efficiencies if native groundwater is brackish</li> </ul>	<b>Heterogeneous</b> <ul style="list-style-type: none"> <li>• Lower recovery efficiencies if native groundwater is brackish</li> <li>• In karstic and fractured rock systems, limited ability to contain recharged water</li> </ul>
<b>Salinity of groundwater</b>	<b>Fresh</b> <ul style="list-style-type: none"> <li>• Recovery efficiency not limiting</li> <li>• Requirement to protect wider range of beneficial uses of aquifer (higher treatment costs)</li> </ul>	<b>Saline</b> <ul style="list-style-type: none"> <li>• Recovery efficiency can limit effectiveness</li> <li>• Less beneficial uses to protect, so treatment need be less onerous</li> </ul>
<b>Lateral hydraulic gradient</b>	<b>Gentle</b> <ul style="list-style-type: none"> <li>• Recharged water contained closer to point of recharge</li> </ul>	<b>Moderate to steep</b> <ul style="list-style-type: none"> <li>• Recharged water dispersed down-gradient and lower recovery efficiency in saline native groundwater</li> </ul>
<b>Consolidation</b>	<b>Consolidated</b> <ul style="list-style-type: none"> <li>• Easier to complete wells</li> <li>• Easier to maintain recharge wells to prevent irrecoverable clogging</li> </ul>	<b>Unconsolidated</b> <ul style="list-style-type: none"> <li>• Screens required for injection and recovery wells</li> <li>• Land subsidence a consideration</li> </ul>
<b>Aquifer mineralogy</b>	<b>Unreactive with recharge water</b> <ul style="list-style-type: none"> <li>• Recovered water quality unaffected by geochemical reactions with aquifer matrix</li> <li>• Likelihood of clogging of injection wells is sometimes increased</li> </ul>	<b>Reactive with recharge water</b> <ul style="list-style-type: none"> <li>• Consider metal (eg arsenic) mobilisation, iron and H<sub>2</sub>S effects on recovered water and groundwater</li> <li>• In carbonate aquifers, less onerous treatment required to avoid clogging of injection wells</li> </ul>
<b>Redox state of native groundwater</b>	<b>Aerobic</b> <ul style="list-style-type: none"> <li>• Higher rates of inactivation of pathogens and biodegradation of some endocrine disrupting chemicals</li> </ul>	<b>Anaerobic</b> <ul style="list-style-type: none"> <li>• Higher biodegradation rates for trihalomethanes</li> </ul>

**Appendix D Schematic of types of managed aquifer recharge (adapted from Dillon 2005).**

