Conjunctive use and management of groundwater and surface water within existing irrigation commands

the need for a new focus on an old paradigm

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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
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- **No.12 -** Groundwater and climate change adaptation

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GROUNDWATER GOVERNANCE: A Global Framework for Country Action
GEF ID 3726

Thematic Paper 2: ***Conjunctive use and management of groundwater and surface water within existing irrigation commands: the need for a new focus on an old paradigm***

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1. Introduction

Conjunctive use of groundwater and surface water in an irrigation setting is the process of using water from the two different sources for consumptive purposes. Conjunctive use can refer to the practice at the farm level of sourcing water from both a well and an irrigation delivery canal, or can refer to a strategic approach at the irrigation command level where surface water and groundwater inputs are centrally managed as an input to irrigation systems. Accordingly, conjunctive use can be characterized as being planned (where it is practiced as a direct result of management intention – generally with a top down approach) compared with spontaneous use (where it occurs at a grass roots level – generally with a bottom up approach). The significant difference between unplanned and planned conjunctive use, and the approach governance must take to maximize the potential benefits from such use, is explored within this paper. Where both surface and groundwater sources are directly available to the end user, spontaneous conjunctive use generally proliferates, with individuals opportunistically able to make decisions about water sources at the farm scale.

The planned conjunctive use of groundwater and surface water has the potential to offer benefits in terms of economic and social outcomes through significantly increased water use efficiency. It supports greater food and fibre yield per unit of water use, an important consideration within the international policy arena given the critical concerns for food security that prevail in many parts of the world. At the resource level, groundwater pumping for irrigation used in conjunction with surface water provides benefits that increase the water supply or mitigate undesirable fluctuations in the supply (Tsur, 1990) and control shallow water-table levels and consequent soil salinity.

The absence of planners and of a strategic agenda within governments, to capitalize on the potential for planned conjunctive use to support these needs, is generally a significant impediment to meeting national and international objectives as they pertain to food and fibre security. There is an urgent need to maximize production within the context of the sustainable management of groundwater and surface water. The challenges posed in some ways reflect the evolution in objectives and management approaches that have been, and remain, common to irrigation development throughout the world.

Many existing irrigation commands source their water supply from both the capture of catchment runoff and aquifer systems. Typically, water has been sourced from either surface or groundwater supplies, with the primary supply supplemented by the alternative source over time. Accordingly, governance settings, infrastructure provisions and water management arrangements have emphasized the requirements of the primary source of supply, inevitably requiring the "retrofitting" of management approaches onto existing irrigation commands to incorporate supplementary water sources over time. Optimizing the management and use of such resources, which have been developed separately will in some situations require substantial investment in capital infrastructure and reform of institutional structures. Put simply, planned conjunctive use is relatively simple with *greenfield* (or new development sites), but significantly harder to achieve within existing hydro-physical and institutional/social systems.

Whilst these challenges and the associated benefits of a strategically planned approach are well understood and the subject of numerous reports on conjunctive use management, the current

status of water management and planning around the world suggests that little has been achieved in its widespread implementation. This paper explores the reasons underpinning the apparent poor approach to full integration in the management and use of both water sources, and the absence of more coordinated planning. It is the authors' view that there remain significant gaps in water managers' understanding as to what aspects of the contemporary management regime require overhaul to achieve integrated management and the improved outcomes that could be expected, as compared with separate management arrangements. Such lack of understanding is an important impediment to the governance, institutional and physical infrastructure reforms whereby planned conjunctive use could improve existing management and regulatory arrangements. Reforms may also be impeded by different 'ownership' models of groundwater and surface water delivery infrastructure and the associated entitlement regime (i.e. private and /or public); a situation that has implications for social and institutional behaviour and ultimately the adoption of a conjunctive management approach.

This paper is intended to provide insight into these barriers to adoption and hence provide a new focus on an old paradigm; a focus intended to make progress with the objective of improved water management and water use efficiency and so support longer term outcomes in the form of improved food security in critical parts of the world.

Part 1: Baseline

2. Concepts and misconceptions of conjunctive use

In most climates around the world, precipitation, and consequently peak river discharge, occurs during a particular season of the year, whereas crop irrigation water requirements are at their greatest during periods of low rainfall when unregulated stream flows are significantly lower. For many irrigation systems, water supply is aligned with crop water requirements through the construction and management of dams, which capture water during periods of high flow, enabling regulated releases to meet crop water requirements. However, the construction, operation and distribution of water from dams are inherently costly undertakings that have social and ecological impacts upon communities and the environment in and on which they are built. Furthermore, dams and the associated distribution systems are commonly subject to high system losses through evaporation and leakage, though it is debateable whether the latter is actually detrimental given that it often contributes substantially to groundwater recharge.

Conversely, under natural recharge regimes, groundwater storage requires no infrastructure, the aquifer serving as the natural distribution system. The point of irrigation, in a groundwater-fed irrigation command, is commonly opportunistically located close to the groundwater extraction point, which in turn is integrated into on-farm irrigation infrastructure. Under a sustainable extraction regime, groundwater of a suitable quality can provide a reliable source of water either as a sole supply of water, or to supplement alternative sources. Commonly, the large storage to annual use ratio typical of many regional aquifers means that the reliability of supply from groundwater is less affected by seasonal conditions than are surface water systems, and may indeed provide significant buffering against droughts. However, most intensively used groundwater systems (within

the context of irrigation) are located in the semi-arid parts of the world and are characterized by relatively low annual recharge. Then the ratio of annual use to long-term annual recharge becomes the predominant measure of sustainability for these systems, independent of aquifer storage. Whilst providing a large storage and natural distribution system, aquifers are, generally speaking, unable to capture a significant portion of runoff arising from large rainfall events. Aquifers therefore do not annually harvest water on a scale that justifies the construction and operation of centralized water delivery systems based on groundwater alone.

These specific characteristics of surface and groundwater resources have important implications for the optimal design and operation of irrigation systems. However, the benefits and limitations are rarely fully considered in the optimization of system design. Rather, supply design is normally focused upon one source of water, with conjunctive use often coming as an 'after thought'. Hence, infrastructure and management responses are retrofitted to existing arrangements.

'Conjunctive use', as for many such technical terms, is the subject of a range of definitions. It is defined by Foster *et al*. (2010) as a situation where "both groundwater and surface water are developed (or co-exist and can be developed) to supply a given ... irrigation canal-command – although not necessarily using both sources continuously over time nor providing each individual water user from both sources". Alternatively FAO (1995) describes it as follows: "Conjunctive use of surface water and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economical effects of each solution and to optimise the water demand/supply balance".

Considering both of these definitions, the aim of conjunctive use and management is to maximize the benefits arising from the innate characteristics of surface and groundwater water use; characteristics that, through planned integration of both water sources, provide complementary and optimal productivity and water use efficiency outcomes.

At the farm scale, conjunctive use is implemented on a day-to-day basis with 'management' characterized by low- or micro-level decisions incorporating factors such as resource availability, costs of delivery to the crop, tradability of unused allocation and water quality. Collectively, these factors contribute to minimizing costs, optimizing production and maximizing net profitability. However, at the irrigation command level, planned conjunctive water use and management aims for higher-level objectives. Planned conjunctive use is expected to optimize productivity and equity in the management of surface water and groundwater resources (World Bank 2006) and to promote economic, environmental and social sustainability.

Depending on the relative volumetric mix of the two resources, and on the manner in which associated irrigation has been historically developed, the nature of conjunctive use at any one irrigation command will be significantly different. For example, management approaches must be different where 90 percent of the available water is from one of the two resources, as compared to the situation where neither resource supplies a majority. Also subtly, groundwater can have three separate roles within a conjunctive management framework: it can be used as an alternative method to distribute water across irrigation commands; it can be used as a storage mechanism to smooth out the supply/demand balance either across seasonal patterns of water availability, or across decadal variability in climate; or it can be used to manage shallow water tables to reduce

salinization and waterlogging. Management (and governance) approaches must be aware of these subtleties in attributes and plan accordingly.

Within this context, Suhaquillo (2004) discusses the use of aquifer storage and the partitioning of its use into artificial recharge *versus* the alternate use of groundwater and surface water depending on seasonally available water. Related to Suhaquillo's partitioning, an important consideration when conjunctively managing surface water and groundwater is the degree of connection between the two water resources – or the overall resource 'connectivity'. Conjunctive use refers to the way in which water resources are managed, whereas a 'connected system' refers to an environment where surface water and groundwater are effectively one connected resource. Most conjunctive use systems use the connectedness of the systems to the advantage of the user; however, natural connectedness is not a necessary feature. Engineered intervention can modify the degree of connectedness where it is desired and economically beneficial.

It is also important to note that, fundamentally, connectivity has nothing to do with conjunctive management. One is a physical attribute of the water system; the other is a form of management. However, they are related in that recognition of connectivity provides the context and framework within which conjunctive management should be planned and undertaken. When groundwater is extracted from a connected system, it may induce recharge from the surface water body, reducing the volume of available surface water. In all circumstances, however, the important consideration for management is the time lag for the effects of use of one resource to be transmitted to the other resource, regardless of how natural or engineered the connectivity. Where time lags are long, specific management challenges are evident and present major impediments. Similarly, when surface water is diverted from a connected system, it can reduce aquifer recharge and therefore the availability of suitable quality groundwater for extraction. If surface water and groundwater are managed separately in connected systems, care must be taken to avoid 'double accounting' when allocating surface water and groundwater from the one connected resource.

Whilst the aquifer provides a natural storage system to source groundwater during periods of demand, optimal management may take advantage of unutilized storage capacity through Managed Aquifer Recharge (MAR) whereby recharge is enhanced for later recovery. From a conjunctive use perspective, such a management approach enables surplus surface water to be captured (during high-flow events) and utilized at times when the dam or streamflow is depleted or when water is required for other purposes. Groundwater recharge enhancement can be done via injection down recharge wells, storage of water in infiltration basins or slowing the natural flow of surface waters to induce additional groundwater recharge (Table 1). An example of this approach is found on the Al Battinah coastal plain of eastern Oman where highly episodic *wadi* flood flows are captured by dams, and the retained water is encouraged to recharge the productive gravel aquifer underlying the area. However, in general, aquifers rarely offer large enough storage capacity for absorbing large volumes of floodwater in a short period of time (FAO, 1995).

The use of artificial recharge (or MAR) as a management option couples the attributes of the aquifer system with those of the surface water system without relying upon the natural hydrological regime of the water cycle. In effect, it decouples the need for physical connection between surface water and groundwater resources through engineering interventions. MAR as an adjunct to conjunctive management would in most cases only be likely to occur through coordinated planning which may

range from village-scale low-technology water harvesting approaches, to technically sophisticated approaches (as increasingly being adopted in the developed world). Irrespective of the degree of technical sophistication, the planning requirements associated with a successful MAR initiative are such that it is unlikely to be adopted where spontaneous 'farm scale' conjunctive use prevails.

Table 1: Summary of types of aquifer recharge enhancement strategies (Foster *et al*. 2003).

Type	General Features	Preferred Application
Water harvesting	**Dug shafts/tanks** to which local storm runoff is led under gravity for infiltration	In villages of relatively low-density population with permeable subsoil
	Field soil/water conservation through terracing/contour ploughing/afforestation	Widely applicable but especially on sloping land in upper parts of catchments
In-channel structures	**Check/rubber dams** to detain runoff with first retaining sediment and generating clearwater	In gullies with uncertain runoff frequency and high stream slope
	Recharge dam with reservoir used for bed infiltration and generating clearwater	Upper valley with sufficient runoff and on deep water-table aquifer
	Riverbed baffling to deflect flow and increase infiltration	Wide braided rivers on piedmont plain
	Subsurface cut-off by impermeable membrane and/or puddle clay in trench to impound underflow	Only wide valleys with thin alluvium overlying impermeable bedrock
Off-channel techniques	**Artificial basins/canals** into which storm runoff is diverted with pre-basin for sediment removal	On superficial alluvial deposits of low permeability
	Land spreading by flooding of riparian land sometimes cultivated with flood-tolerant crops	On permeable alluvium, also with flood relief benefits
Injection wells	**Recharge boreholes** into permeable aquifer horizons used alternately for injection/pumping	Storage/recovery of surplus water from potable treatment plants

At the general level, the benefits attributed to optimizing conjunctive use of surface and groundwater have been investigated over many years through theoretical modelling and studies of physical systems. These benefits take the form of:

economic gains;
increases in productivity;
energy savings;
increased capacity to irrigate via larger areas;
water resource efficiency; and
infrastructure optimisation.

However, there are few published analyses of the actual socio-economic benefits that can be attributed to the implementation of conjunctive use management in specific irrigation commands. This is a major impediment to further communicating the positive messages regarding conjunctive use. However, an example of such studies includes Bredehoeft and Young (1983), who modelled a twofold increase in net benefit arising from conjunctive management. Another is the Agriculture and Rural Development Group, World Bank (2006), which reported a 26 percent increase in net farmer income, substantial energy savings, increased irrigation and substantial increase in irrigated crop area for Uttar Pradesh, India, as a result of conjunctive management of monsoon floodwaters in combination with a regional groundwater system.

2.1 Systems that occur spontaneously and systems that are planned

The introductory section of this paper highlights the two fundamentally different approaches to conjunctive use management, however, there is a continuum in the way that conjunctive management evolves from spontaneous (or incidental/unplanned) conjunctive use at one end, to planned conjunctive management and use at the other.

Planned conjunctive management and use of surface water and groundwater are usually practiced at the State or regional level and can optimize water allocation with respect to surface water availability and distribution, thus reducing evaporative losses in surface water storages and minimizing energy costs of irrigation in terms of kWhr/ha (Foster *et al.*, 2010). Planned conjunctive management is best implemented at the commencement of a development although experience has shown optimal outcomes may be difficult to achieve when attempts are made to redesign and retro-fit the approach, once water resource development is well advanced.

Where groundwater and surface water are used conjunctively in various parts of the world, spontaneous use prevails. Foster and Steenbergen (2011) emphasize that spontaneous conjunctive use of shallow aquifers in irrigation-canal-commands is driven by the capacity for groundwater to buffer the variability of surface water availability enabling:

greater water supply security;
securing existing crops and permitting new crop types to be established;
better timing for irrigation, including extension of the cropping season;
larger water yield than would generally be possible using only one source;
reduced environmental impact; and
avoidance of excessive surface water or groundwater depletion.

Foster *et al.* (2010) report that the most common situation in which spontaneous conjunctive use of surface water and groundwater resources occurs is where canal-based irrigation commands are:

inadequately maintained and unable to sustain design flows throughout the system;
poorly administered, allowing unauthorized or excessive off-takes;
over-stretched with respect to surface water availability for dry season diversion; and
tied to rigid canal-water delivery schedules and unable to respond to crop needs.

Additionally, spontaneous conjunctive use is also driven to a large degree by poor reliability of water quality in surface water supply cannels. Wells become an insurance against this unreliability. Poor water quality is a common factor at the tail of most irrigation canal systems and usually reflects poor infrastructure maintenance. These factors lead to inadequate irrigation services. As a consequence, the drilling of private waterwells usually proliferates, and a high reliance on groundwater often follows (Foster *et al.*, 2010).

Foster and Steenbergen (2011) report spontaneous conjunctive groundwater and surface water use in Indian, Pakistani, Moroccan and Argentinean irrigation-canal commands which have largely arisen due to inadequate surface-water supply to meet irrigation demand. Many other examples from developed countries also show that it is not simply a developing country problem – it is an inherent problem wherever canal-based irrigation is practiced and where there are challenges in terms of reliability of water supply and quality.

In summary, the spontaneous approach to the conjunctive use of surface and groundwater sources reflects a ’legacy of history’. The focus for green-field irrigation developments is primarily access to water, rather than the efficient and optimal use of that water; a consideration that does not gain attention until competition for water resources intensifies. Advancing beyond the farm-scale spontaneous access to each water source to a planned conjunctive management approach entails significant technical, economic, institutional and social challenges that can only be overcome with an effective governance model.

2.2 Types of aquifers

Conjunctive use can be practiced in a large number of combinations of surface water and groundwater regimes. Generally, surface water systems have high annual flow volumes and tend to be regulated, perennial rivers, whereas groundwater systems show much more variation. There is, however, a distinction between those integrated resources systems where conjunctive use has developed spontaneously and those where it is planned.

Planned conjunctive use systems can be developed on most groundwater regimes where there is adequate storage and well yield to enable efficient utilization of both the supply and demand side of the equation. The only distinction, effectively, is the degree to which the aquifer system provides a substantial natural connectivity to the surface water system, compared with those where constraints in hydrological linkages require significant engineering to overcome limitations in connectivity. Where the degree of connectivity between surface water and groundwater is poor or limited, engineered solutions can be used to transfer water from one resource to another. Within such aquifers, these inherent conditions may require MAR schemes to be adopted, sometimes on a large scale, subject to economic viability and to a range of attributes of the aquifer/source water required for feasible MAR. Such planned and engineered solutions ultimately are dependent on the level of investment available by either government or the private sector, and the productivity benefits that can be achieved.

The types of aquifers involved in conjunctive use regimes that are spontaneous in nature are usually restricted to types that exhibit certain attributes. Generally, such systems are broad regional alluvial aquifers that have good connection either with associated large rivers or with irrigation command areas, both of which have the potential to provide a significant source of recharge. Previous work has documented that the potential for conjunctive use varies considerably with the type of aquifer involved (Foster et al., 2010). These types can be partitioned into four major groupings (

Table 2).

This typology was further refined (Foster and van Steenbergen, 2011: Figure 1) to include variation associated with position in terms of the longitudinal profile of the alluvial system; namely, outwash and peneplain, floodplain and coastal plain. Each of these settings provides a different style of aquifer material, depth to water table and surface water-to-groundwater connectivity.

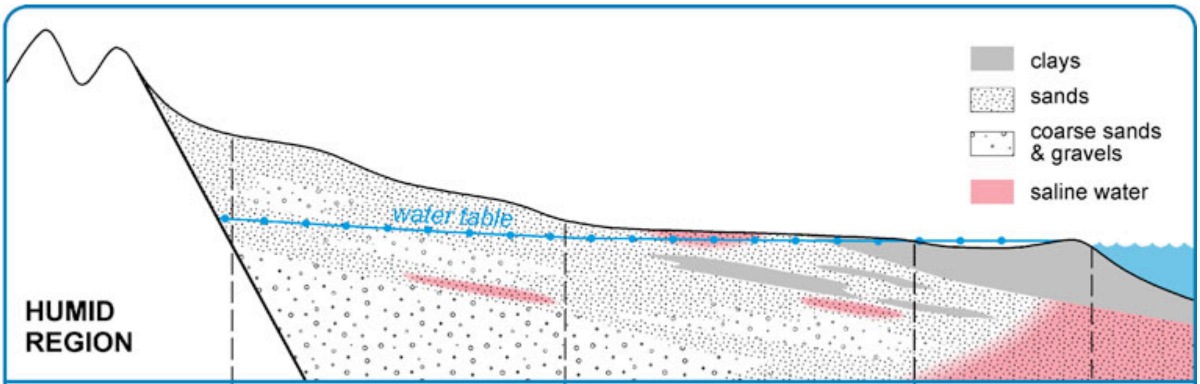
Table 2: Aquifer typology (after Foster *et al.*, 2010)

Aquifer Type	Example Location
Upstream humid or arid outwash peneplain	Indian Punjab-Indus Peneplain, Upper Oases Mendoza – Argentina Yaqui Valley, Sonora – Mexico
Humid but drought-prone middle alluvial plain	Middle Gangetic Plain – India Middle Chao Phyra Basin – Thailand
Hyper-arid middle alluvial plain	Middle Indus Plain – Pakistan Lower Ica Valley – Peru Tadla – Morocco Tihama – Yemen
Downstream alluvial plain or delta with confined groundwater	Ganges Delta – Bangladesh Lower Oasis Mendoza – Argentina Nile Delta – Egypt

Clearly, there are some minimum requirements that will act as a threshold for groundwater to be seriously considered as part of a conjunctive use system. These requirements relate to the aquifer attributes that control the size of the resource, the rate at which it can yield groundwater and the economic viability of extraction. This means that aquifer size (storage ability), aquifer or basin effective hydraulic conductivity and the depth to the water table/potentiometric surface are critical. So too is water quality.

2.3 Highly *versus* poorly connected systems

When groundwater and surface water are hydrologically connected, the interchange of the resource between the systems requires consideration during the management process. Accordingly, it is an aspect that must be considered within a conjunctive use framework, as it can shape the available options and hence define the optimal approach to conjunctive management.



ALLUVIAL SETTING	OUTWASH & PENE-PLAIN	FLOOD PLAIN	COASTAL PLAIN
Hydrogeological Conditions	unconfined high-yielding aquifer with increasingly deep water table but rapid vertical recharge	multi-layered aquifer with shallow water table and moderate waterwell yields but with some 'rejected recharge'	confined aquifer with very restricted vertical recharge and reducing effective thickness
Water Resource Management Implications as in Humid Regions	much care needed to avoid 'double-accounting' due to infiltration of surface water via irrigation systems	poorly-managed surface water irrigation results in soil water-logging/ salinisation; river baseflows used for irrigation can be greatly reduced by 'upstream' consumptive groundwater irrigation use	aquifer highly vulnerable to saline water intrusion on intensive exploitation and reversal of natural hydraulic gradients
Water Resource Management Implications as in Hyper-Arid Regions	high soil-profile salinity under natural vegetation mobilised when irrigated cultivation introduced	groundwater at depth naturally saline with freshwater restricted to lenses beneath major rivers/irrigation systems	surficial aquitard may also contain saline water which can seep downward

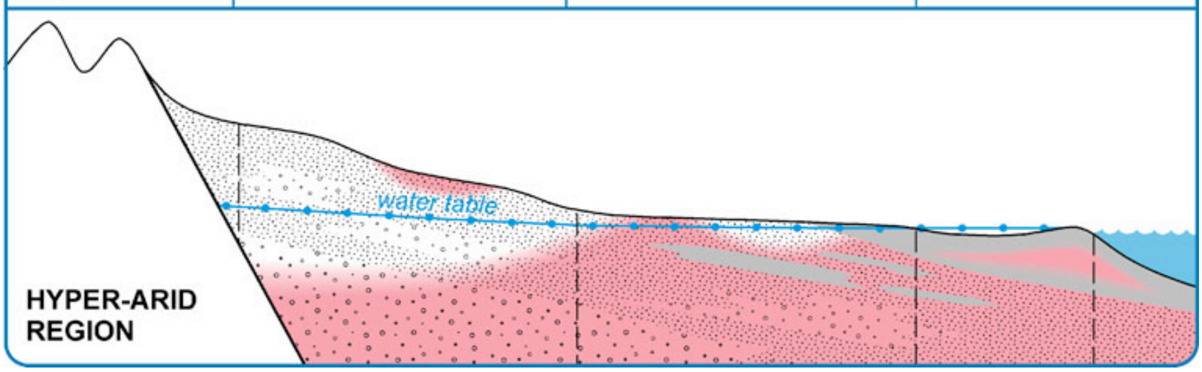


Figure 1: Schematic long-profile of a typical alluvial groundwater system in a humid region detailing the variation in groundwater-surface water connectivity and salinization hazards (from Foster *et al.*, 2011)

Connectivity comprises two important components: the degree of connection between the two resources and the time lag for extraction from one resource to impact upon the other. A highly connected resource would be one where the degree of connection is high and the time lag for transmission of impacts is very fast. A fundamental tenet of connectivity understanding is that, essentially, all surface water and groundwater systems are connected and that it is just a matter of time for impacts to be felt across the connection. Important exceptions to these truisms are that of canal-dominated irrigation commands, where the water table is below the water level in the canal system or where the water table is shallow and groundwater extraction is capturing losses to evapotranspiration. In such areas recharge may also be dominated by irrigation-induced rootzone drainage, and hence vertical unsaturated zone processes may control the interaction/connectivity process. In these latter areas, the canal distribution systems may provide a significantly reduced contribution to groundwater extraction.

A large body of research and investigation has been undertaken on the issue of connectivity and this will not be dealt with in any detail here. The salient issue for conjunctive management, especially in a planned environment, is to understand the nature of connectivity as a factor in resource use optimization and to ensure that connectivity is understood when considering water resource accounting in a conjunctively managed water system.

Figure 2 provides examples of connected gaining and losing streams and of streams that fluctuate between these two situations (a, b and d respectively). It also indicates that the head difference between the river and the aquifer determines the direction of flow. The rate of flow between the river and aquifer will depend on the hydraulic conductivity of the aquifer and the hydraulic conductance of the bed of the river. Figure 2 (c) provides an example of a stream that is connected to the adjoining aquifer through an unsaturated zone; this situation is usually found in arid areas. The interchange of water between surface water and groundwater is controlled by the hydraulic conductivity of the unsaturated zone (SKM, 2011).

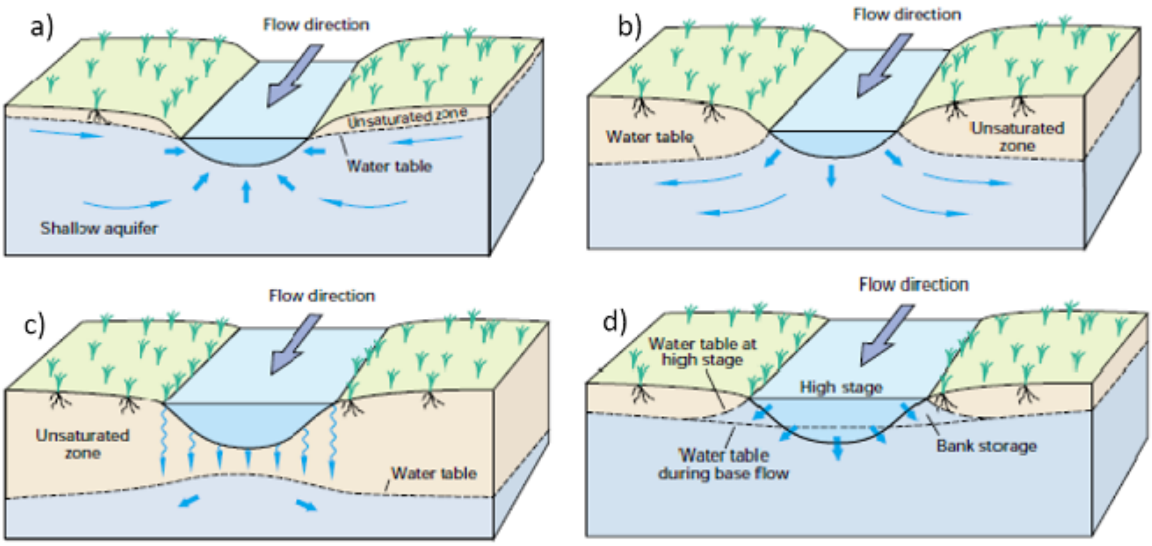


Figure 2: Connectivity relationships: a) gaining connected system; b) losing connected system; c) disconnected system; d) fluctuating connected / disconnected system (modified after Winter *et al.*, 1998)

The timing of the impacts is very important. Bredehoeft (2011) has shown that timing is important to water resources managers whether the impacts from groundwater pumping on a stream occur within an irrigation season, or over a longer period. Connectivity will control the timing for groundwater recharge and the timing of changes in discharge from groundwater to the streams due to groundwater abstraction.

Figure 3 shows a simple example of the relationship between groundwater pumping and the timing of impacts felt in a connected surface-water system. In this hypothetical example, the full impact time (t_{100}) has not been specified, but it can vary from very short (days) to very long (many decades). It is important to attempt to understand or calculate the likely t_{100} time so impacts can be accounted for within integrated water resource plans.

Box 1. How to avoid double accounting

As previously discussed in this paper, 'double accounting' relates to the dual allocation of a single parcel of water. It is a common occurrence throughout the world due to the evolution of water resource development and associated regulatory arrangements, and it may reflect an absence of a proper water resource assessment, poor understanding of the water balance, or the undertaking of independent resource assessments for surface water and groundwater. Two common situations occur.

Firstly, when surface-water-based irrigation causes recharge to the groundwater system. The groundwater recharge is seen as a 'loss' from a surface-water point of view. A typical water resource management response may be to invest in improved sealing canals or constructing pipelines, however this may not be the most efficient response. In situations where groundwater recovery is financially viable, a more efficient approach may be to utilize aquifer storage capacity and the diffuse distribution of the resource provided by the groundwater system. If in such situations, canal leakage has already been allocated to surface water users, then it should not also be allocated to groundwater users. Instead, mechanisms such as trade should be used to transfer entitlements from one user to another, and hence maintain the integrity of the water accounting framework. Furthermore, any decision to reduce leakage through canal lining, and hence reduce recharge, would require revision to the water resource assessment and may require appropriate adjustments to entitlements, particularly if such recharge had been allocated to groundwater users.

Secondly, the classical surface water/groundwater interaction situation is where groundwater discharges to become base flow. Considered in isolation, this may be deemed as a "loss" from a groundwater management perspective and a justifiable basis for allowing groundwater pumping to substantially reduce stream flow. Similarly from a surface-water management perspective, the significance of groundwater discharge in maintaining stream flow during the dry season may be poorly recognized. There are many examples in the literature (for example, Evans, 2007) where the implications of not recognizing such interaction have contributed to the depletion of rivers around the world. The assessment of the interaction requires an integrated resource assessment, with the water balance taking into account all extraction regimes and the consequential impacts on both groundwater and surface water resources.

Eliminating double accounting requires integrating water entitlements with a water balance that reflects the full hydrological cycle, and hence fully appreciating the amount and timing of the interaction between groundwater and surface water. It is also critical to appreciate the temporal variability of the process. In this case, it is important that the conjunctive planning time frame be long term, for example 50 years. Short-term planning to meet political or social objectives will not achieve effective conjunctive management. There are some relatively rare situations where there is effectively no interaction between groundwater and surface water. In such situations, conjunctive management is relatively less complicated, but nonetheless important in terms of achieving optimal water management outcomes.

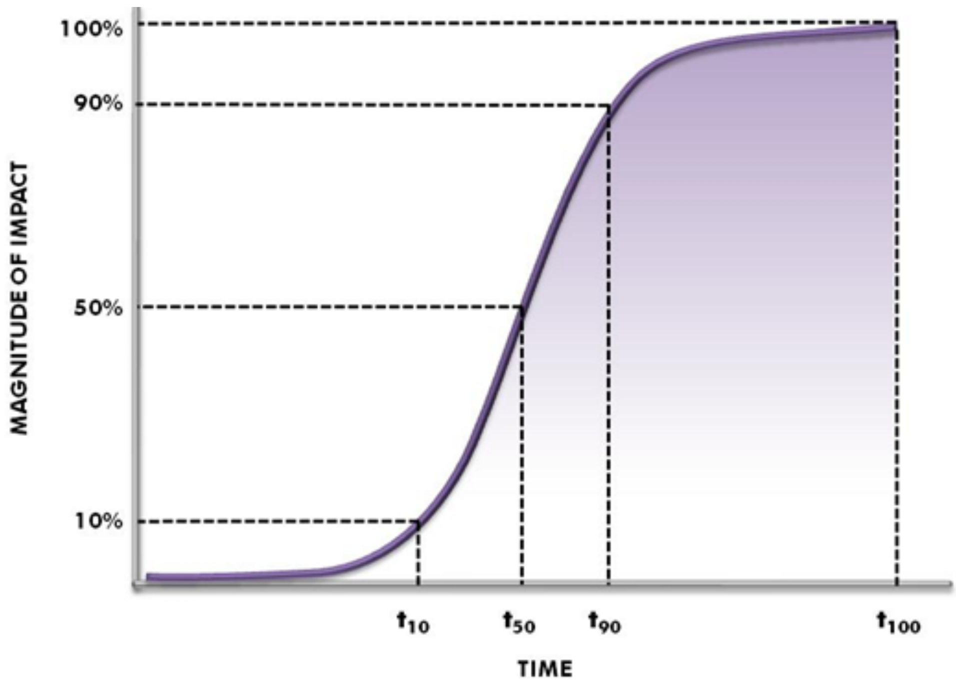


Figure 3: Simplified groundwater pumping time and impact relationship

Within connected systems, groundwater abstraction will therefore induce aquifer recharge from the surface water body reducing the volume of available surface water, although as shown in Figure 3, the magnitude of the impacts will be a function of time, which in turn will be dependent upon the properties of the associated hydrology. Similarly, when surface water is diverted from a connected system it can reduce aquifer recharge and therefore the availability of suitable quality groundwater for extraction. If surface water and groundwater are managed separately in connected systems, care must be taken to avoid 'double accounting' where the same volume of water is potentially attributed to both the surface and groundwater resource. The issue of double accounting is explored in more detail elsewhere in this paper (Box 1), but it is worth noting within this section that it is generally reflected in situations where streamflow leakage is accounted both as streamflow and as groundwater recharge. Similarly, baseflow can be accounted both as groundwater discharge and as normal streamflow.

In cases where the two water resources are highly connected with short time lags, conjunctive management may be supported by a transparent water-accounting framework that can be reported on for both surface and groundwater on an annual basis. It may provide flexibility in the way in which surface and groundwater is allocated on an annual basis, and could facilitate the development of a robust two-way water-trading regime between the groundwater and surface water system, providing third-party impacts are understood and effectively managed.

Conjunctive management within an environment where surface and groundwater systems are poorly connected is unlikely to provide such a degree of integration. Whilst there are opportunities for integration (such as the application of MAR discussed previously) and for taking advantage of the unique attributes of groundwater and surface water, such as storage, distribution and reliability in dry periods (also identified earlier), the opportunities and benefits that have the potential to arise from conjunctive use will be different, reflecting differences in the hydrological environment. In other words, within poorly connected systems, conjunctive management will be framed around the

task of complementary and integrated management of water use, without the need for such integration to consider hydrological linkages of the water sources. This is modified, however, where engineered solutions enable better (anthropogenic) connection between the two parts of the water system.

2.4 Salinity control as a driver

Major benefits and contributing drivers to the establishment of conjunctive use in irrigation commands are water-table control and ensuing soil-salinity management. As has been shown throughout India and Pakistan, groundwater extraction from unconfined aquifers supports the management of soil salinity by providing an opportunity for leaching of accumulated salts. In these cases, the factors discussed above that drive development of the groundwater system (primarily hydraulic conductivity) are not as important as the benefits of sub-surface drainage. It is important that governance arrangements clearly acknowledge these benefits, where applicable, and that planning also considers the management of salt where abstracted water supplies are integrated into the supply system.

2.5 Technical and management differences between surface water and groundwater

The characteristics of the two primary water sources associated with conjunctive use and management (i.e. groundwater compared with surface water) are inherently different; differences that must be appreciated when optimizing their use. A summary of typical characteristics associated with groundwater and surface water resources is provided in Table 4.

Table 4: Typical characteristics of groundwater and surface water

Characteristic	**Groundwater**	**Surface Water**
Response time	Slow	Quick
Time lag	Long	Short
Size of storage	Large	Small
Security of supply	High	Low
Water quality	Poor	Good*
Spatial management scale	Diffuse	Linear
Ownership	Private	Public
Flexibility of supply	Very flexible	Not flexible

*Whilst surface water supplied within irrigation areas is generally of a higher quality than groundwater, it is worth noting that surface water quality often deteriorates toward the downstream end of the distribution system if the irrigation delivery system receives drainage return flows. This applies particularly in areas where drainage systems are subject to saline groundwater inflows.

Given the extent and diversity of irrigation systems covering a vast range of physical environments throughout the world, there are many situations where the characteristics of the surface/groundwater components of local water resources are represented by the 'typical' characteristics presented above. Nonetheless, physical differences and differences in the history of development of the two resource types provide both challenges and benefits to conjunctive

management and use. To make progress on conjunctive management, the specific characteristics of groundwater and surface water in the target region must be assessed. Such an assessment includes the social, economic and environmental aspects (the so-called 'triple bottom line') so as to evaluate how the particular characteristics of the hydrological environment can be integrated to achieve optimum outcomes. It is almost mandatory in current times to ensure that water resources management is undertaken not only in an integrated manner, but also cognisant of triple-bottom-line issues.

2.6 Overview of major irrigation systems throughout the world where both surface water and groundwater are used

Generally, conjunctive use, especially in the spontaneous form, has developed on the major alluvial plains and their associated aquifers of the world (as discussed above). Foster *et al.* (2010) contend that the above-mentioned settings, together with variations of average rainfall and geomorphological position, control the potential for conjunctive use for irrigated agriculture. A further driver appears to be water availability, or more pertinently, water scarcity – the pressure to find and utilize other water sources increases as water becomes scarce. Nevertheless, the scale of the adoption of conjunctive use is generally controlled by the scale of the groundwater system.

Historically, surface water has been the primary source in the majority of such systems, with groundwater providing an alternative source when surface water availability is low, particularly during periods of drought. However, with increasing demand for water, the value of groundwater is achieving greater recognition, becoming in many areas an important primary source of water supply for irrigation. The increased value for groundwater more generally has been driven by growth in irrigated areas that were traditionally supplied from surface water, hence increasing the demand from these historic sources.

The use of groundwater for irrigation has generally increased worldwide (in some cases exponentially) since the 1950s. For instance, surface water withdrawals accounted for 77 percent of all irrigation in the United Kingdom (UK) in 1950 but, with increasing groundwater development, withdrawals declined to just 59 percent by 2005 (USGS, 2011). Similar patterns are apparent in the developing world, although surface water canal commands generally remain at the heart of irrigated agricultural districts, with groundwater being used mainly in times of surface water shortage.

There are a number of different factors influencing increased groundwater extraction with the dominant drivers being a function of local circumstance. Some of these important drivers are presented in Table 5. Also included in this table are factors that have contributed to users maintaining surface water as their sole source of supply.

Table 5: Summary of drivers for sole use of groundwater or surface water resources

Drivers of Resource Use	Groundwater Resource	Surface Water Resource
Variable climate	A highly variable climate will typically favour users of groundwater resources, as groundwater characteristically provides a higher reliability of supply than surface water.	
Poor surface water quality	Poor surface water quality (often generated by the irrigation system itself) will favour groundwater use.	
Poor groundwater quality		Surface water will remain the dominant resource when groundwater quality is poor.
Lack of adequate infrastructure	Gaps or failures in infrastructure (or in its operation and maintenance) that delivers surface water to users will favour groundwater use.	
Depth of groundwater resource		Groundwater resources found at significant depths below the surface will incur significant pumping costs and hence often favour the use of surface water resources.
Traditional farming practices	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices.	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices.
Discovery of a new groundwater resource	The discovery of a new groundwater resource will drive groundwater use; particularly in well developed systems where surface water allocations have been capped. It is especially so if there are fewer regulations on groundwater use.	
Economic value associated with production	Where economic return is significant, investment into obtaining additional water from a groundwater resource is more likely to occur.	If the economics in terms of farm income are distorted towards surface water use, farmers will be reluctant to incur additional cost to change water sources or use.
Energy pricing	Subsidized energy costs of pumping can encourage groundwater use	
Technology advances	Advances such as managed aquifer recharge mean that utilization of groundwater resources is often more feasible due to an increase in the volume of available water and security of supply. Also advances in pumping technology can encourage groundwater usage.	
Irrigator	A lack of irrigator education and understanding	A lack of irrigator education and

education and understanding	of the benefits of conjunctive groundwater and surface water use can inhibit deviation from groundwater supply as a sole resource.	understanding of the benefits of conjunctive groundwater and surface water use can inhibit deviation from surface water supply as a sole resource.
Institutional structures	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use, surface water or groundwater (whichever is currently favoured) will remain the primary water source for users.	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use, surface water or groundwater (whichever is currently favoured) will remain the primary water source for users.
Shallow water-table mitigation	Large volumes of irrigation recharge can lead to artificially high water-table levels, which threaten surface and groundwater quality and the environment itself. Government incentives that encourage groundwater use as a mitigation measure ultimately drive groundwater use.	

In surface-water irrigation commands, there can be differences in water security based on how close the particular farm off-take is to the primary diversion canal, especially where the delivery infrastructure is operated (or performs) in an inefficient manner. Those close to the primary source (termed the 'head' of the irrigation command) are likely to benefit from regular supplies whereas those at the end of the delivery system (the 'tail') are subject to the efficiency of the delivery canals and the compliance of other farmers to access rules. In some cases the quality of the delivered water will deteriorate as the delivery system also sources groundwater discharge from irrigation-induced shallow water tables. In such cases, individual wells become an insurance policy against both diminished and uncertain supply and poor water quality.

2.7 Lessons learnt about governance

This paper is essentially about the governance approaches that are required to implement conjunctive use management in irrigation commands. Groundwater governance is defined here as the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision-making between and among different jurisdictional levels – one of which may be global (adapted from Meganck and Saunier, 2007).

There are different implications for governance arrangements depending whether one is retrofitting planned conjunctive use to an existing irrigation command, or whether conjunctive use is being developed in a 'greenfields' situation. These implications will be further developed in a following section, but it is useful to summarize the commonality of current approaches and lessons learnt at this point.

In both cases, the following will be required:

- institutional strengthening to ensure that integrated water management occurs, together with explicit decisions about system management and operation[1];
- commitment to sustainability objectives that target environmental, social and economic outcomes;
- decisions about future investment in infrastructure and cost recovery;
- strong policy and legislative leadership to drive a planned approach, within a compliance culture;
- clear and robust implementation and delivery mechanisms to ensure the central planning and policy approach can be taken through to on-ground action;
- participatory involvement by the grass-roots water users and related stakeholders; and
- technical knowledge of the surface water and groundwater systems to enable efficient use of both resources, as well as capacity building to apply this technical knowledge.

However, irrigation commands where spontaneous conjunctive use has evolved over time will also require a significant investment in planning to enable integration of opportunistic pumping within the optimal conjunctive use framework. This will require (in addition to the above):

- establishment of institutions that provide complementary planning and regulatory functions;
- modification of current behaviour, that may be achieved through –
    - implementation of a compliance management framework;
    - potential use of either market instruments or direct incentives to encourage and effect farmer change; and
    - targeted extension programmes that, through education and demonstrations, enable farmers to realize the on-farm benefits to be provided by the planned approach.

Because spontaneous conjunctive use has usually evolved over time, policy objectives such as sustainability may not be fully evident or understood, unless serious resource depletion is already placing physical constraints on access. Regulated reductions in access may therefore create tensions, highlighting the value in improved understanding by irrigators, and the value in stakeholder involvement within the planning process.

Where conjunctive use has grown up spontaneously around a previously surface-water-dominated irrigation command, one might expect management to be somewhat centralized and rigid. Where it has grown around a strongly groundwater-dominant irrigation command, management approaches may be less rigid and more informal, to the point where there is little regulatory control. Each of these end members will represent particular challenges in achieving a governance model that is able to support a technically robust and appropriately designed conjunctive management model.

[1] Institutionally, international experience is that surface water management is almost always separated from groundwater management, though they may share the same 'head' institution or governing authority. It is the authors' view that major institutional reform is required to bridge this 'divide' not just in name but through planning behaviours and operational arrangements.

Part 2: Diagnostic

3. Examples of successes and failures of conjunctive use

The following sections describe some examples of irrigation commands where conjunctive use of groundwater and surface water resources occur. This chapter draws heavily on the work of GW-MATE (see Foster *et al.*, 2010 and related references) and is by no means exhaustive. Examples are provided as a way of describing the breadth of types of conjunctive use systems currently operating worldwide. It is acknowledged that conjunctive use of groundwater and surface water already occurs in most countries where irrigated agriculture is practiced, in the developed and developing world. However it is also recognized that, whilst conjunctive use is probably the norm more so than the exception, its operation within an integrated water management framework is where adoption is significantly lacking.

It is rare for institutions or commentators to document the failures of conjunctive use management, therefore the following examples focus entirely on successes. However, the lack of documentation of failures is in itself a major impediment to this diagnosis and to the development of improved management of conjunctive use of surface water and groundwater.

3.1 Uttar Pradesh – INDIA

Foster et al. (2010) have described the setting for conjunctive use in the State of Uttar Pradesh in India, which is categorized as a humid but drought-prone middle-alluvial-plain hydrogeological setting (

Table 2 above). The alluvial plains of the Ganges Valley (the Indo-Gangetic Plain) in Uttar Pradesh are underlain by an extensive aquifer system holding groundwater that represents as much as 70 percent of the overall irrigation-water supply. This is one of the largest groundwater storage reserves in the world. Its utilization as a water resource has primarily arisen in response to reduction in supply and unreliable operation of the irrigation canal systems. The aquifers are directly recharged from infiltrating monsoon rainfall but also indirectly from canal leakage and poor applied irrigation efficiency (i.e. excess rates of field application) – a common scenario in such hydrogeological settings.

Increasing groundwater abstraction has resulted in a declining water table, particularly in high intensity 'groundwater exploitation zones', whereas in other areas (in some cases within 10-20 km), flood irrigation and canal leakage have maintained shallow water tables. The decline in water tables in some areas is correlated with evidence of irrigation tubewell dewatering, yield reduction and pump failure, together with hand-pump failure in rural water-supply wells. Conversely, threats arising from shallow water tables elsewhere are evident in around 20 percent of the land area being subject to shallow or rising groundwater levels, with soil water-logging and salinization leading to crop losses and even land abandonment (Foster *et al.*, 2010).

Protocols for the operation of the distributary canal system exist, but they have not been strictly adhered to in the past, and this has contributed to an imbalance in surface-water delivery through the system.

In the light of the challenges posed by rising water tables in some areas and declines in the water resources elsewhere, in the Jaunpur Branch canal-command area in Central Pradesh a 'more planned conjunctive-use approach' is being implemented. The adopted approach uses extensive datasets and associated analysis to understand the hydrogeological, agronomic and socioeconomic situation. Strategies include: attempts to reduce leakage through maintenance of bank sealing in major irrigation canals, enforcing current operational codes, promotion of tubewell use in non-command and high-water-table areas, and investment into research and specialist extension in soil salinity mitigation and sodic land reclamation.

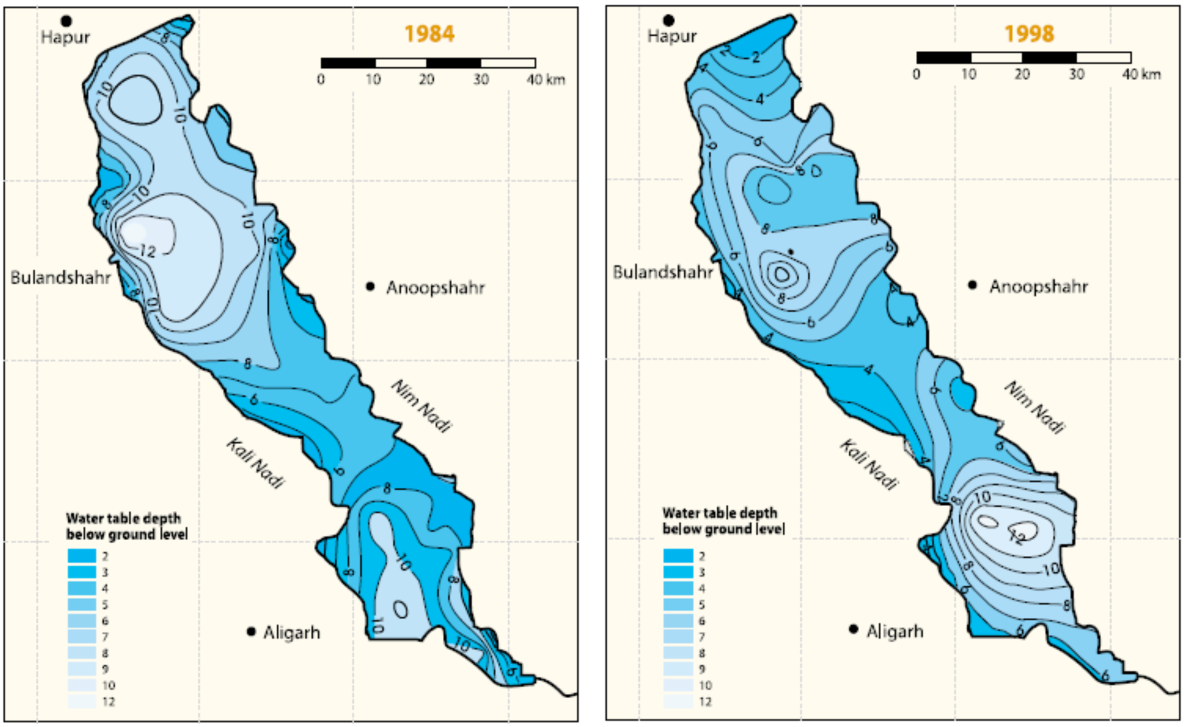


Figure 4: Comparison of water-table depth before (1984) and after (1998) recharge, Uttar Pradesh (from IWMI, 2002). Maps of the Lakhaoti Branch Canal, Utter Pradesh, India, showing post monsoon depth to groundwater before and after recharge management began. Dark blue areas show where groundwater levels are close to the surface.

These activities are being aligned with the pursuit of an appropriate management plan, for which the land surface has been subdivided on the basis of hydrogeologic and agroeconomic criteria into 'micro-planning and management zones'. For each zone a canal reach (e.g. head, mid or tail) is assigned with an indication of current irrigation canal flow and water-table level. The irrigation water service situation, the groundwater resource status and the groundwater management needs are then identified.

This zoning approach allows targeted management actions that range from encouragement of groundwater use in the head end of the irrigation systems where shallow groundwater levels prevail, focusing upon higher value crops, in some areas, and on improving canal-water availability for those at the lower ends of the system. Collectively, these mechanisms are intended to provide a more balanced approach across the canal command (and beyond) and contribute to a sustainable future for agriculture in the region (Foster *et al.*, 2010). Figure 4 above shows the beneficial changes in water-table depth for one such targeted area.

IWMI (2002) describes the situation for the western Indo-Gangetic plain, where, although rainfall ranges between 650 and 1 000 mm annually, only 200 mm naturally percolate through soil layers to recharge underlying aquifers. In this area, like many others in India, groundwater pumping by farmers exceeds recharge (from rainfall and leakage from surface waters – canals and rivers – and application excess). Farmers are at the mercy of monsoon rains, which can fail to provide water when and where it is needed. The high concentration of rainfall, over a 3-month period, means the majority of water runs off the already saturated soil. During the dry season, a lack of canal water means a reliance on pumping from groundwater stores, which are not totally replenished from the previous year, hence further depletion (mining) of the aquifer system.

A 10-year pilot project (the Madhya Ganga Canal Project) undertaken in this area has demonstrated a low-cost way of using the excess surface water during monsoon season by conserving and rejuvenating falling groundwater reserves. The project involved diversion of 234 m^3/s of monsoon waters in the River Ganga to the Madhya Ganga Canal, which feeds both the Upper Ganga Canal system and the Lakhaoti Branch Canal system. Through systems of unlined (unsealed) earthen canals, water is delivered to farmers for irrigation of water-intensive monsoon crop such as paddy rice and sugarcane. The unlined nature of the canal systems and infiltration of excess irrigated water facilitates the recharge of underlying aquifers, in which the water table was raised from an average 12 m bgl to an average 6,5 m bgl. Simulations showed that, without such a conjunctive management approach, levels would have continued to decline to an average depth of 18,5 m bgl over the course of the study.

The conjunctive management of surface water and groundwater has proved productive in terms of the average net income increasing by 26 percent through reductions in pumping costs and improved cropping systems. It has demonstrated a more sustainable system through improved cropping patterns and through more reliable and sometimes new sources of water for irrigation and other uses, such as domestic/industrial supplies (e.g. providing water in previously existing dry pockets). During the dry season, drawdown from groundwater pumping prevents waterlogging and maximizes storage space for recharge during the following year's monsoon.

Unused (often lined) drainage canals constructed in the 1950s to control water logging and floods are also being targeted as a means for diverting monsoon waters across India, either for irrigation, storage and later use or for recharge to underlying aquifers. Modification of previously lined canals can aid their transformation into temporary reservoirs, where 'check structures' at suitable intervals slow down water flow and increase the aquifer recharge capacity of the carrier (Khepar *et al.*, 2000 in IWMI, 2002). In combination with the use of earthen irrigation canals, the use of old drainage networks can maximize water use and storage for very low cost compared to building new infrastructure such as dams (Khepar *et al.*, 2000 in IWMI, 2002).

3.2 Mendoza – ARGENTINA

Foster and Garduño (2006) describe the situation in the Mendoza Aquifers of Argentina, which are also highly developed within and outside existing irrigation-canal commands. The Mendoza Aquifers are characterized by an upstream arid-outwash-peneplain hydrogeological setting (

Table 2 above) and are shown diagrammatically in Figure 5. The aquifers are recharged directly from the Mendoza and Tununyan rivers as they emerge from the Andean mountain chain and indirectly from irrigation canals and irrigated fields.

The General Department for Irrigation (*Departamento General de Irrigacion* – DGI) is the autonomous water resource authority responsible for water management in the entire province, down to the primary canals and the delivery of water to Water Users' Associations (WUAs). Groundwater abstraction is the main source of water for irrigation outside the command of main canals and is used to supplement surface water during times of critical plant demand and in years of low flow.

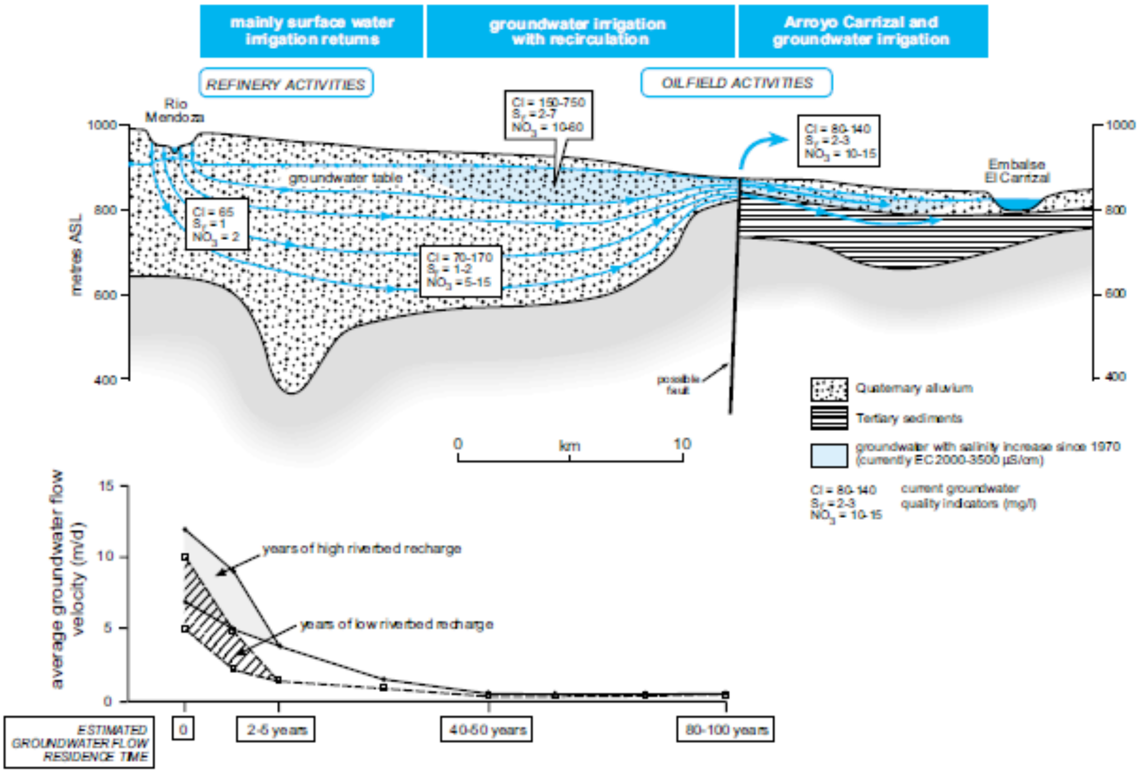


Figure 5: Hydrogeological profile along the flow direction of the Carrizal aquifer system (from Foster and Garduño, 2006)

The DGI's initial approach to groundwater resource management involved:

encouraging irrigation waterwell drilling in areas outside and on the margins of existing irrigation-canal commands; and

permitting waterwell drilling within surface-water irrigation commands, if existing canal allocation did not provide a reliable supply at times of low riverflow and/or maximum plant demand.

Although the strategy was generally a success, problems with high and increasing groundwater salinity in two areas of intensive groundwater irrigation started to emerge. Salinity distribution during 2003-2004 suggested the current groundwater flow, irrigation use and return flow were significant contributors to these problems.

In the Carrizal Valley, the expansion of high-intensity groundwater use for irrigation of export-quality viticulture and fruit production, while efficient due to application of modern irrigation practices, has put pressure on the groundwater system. Six to seven hundred active production wells were reported in the valley in 2006, with consistently elevated electricity consumption reflecting the high dependence on the wells for agricultural irrigation.

In the Montecaseros zone, the second problematic area, the aquifer system has marked layering into sub-aquifer units separated by aquitards. Groundwater salinity in the shallowest of these increased substantially between the 1970s and 1995, instigating a shift to extraction targeting deeper sub-aquifers. However, there has been downward migration of saline groundwater, thought to be related, among other things, to pumping from sub-aquifers the water which is potentially derived from overlying strata, and less so from poorly constructed and/or highly corroded wells providing conduits for brackish water.

When estimated demand exceeded available resources – following continued below-average riverbed recharge amidst concerns around falling water tables, increasing groundwater salinity in some areas, competition amongst groundwater users and between others dependent on downstream groundwater discharge –, the Carrizal Valley and Montecaseros zone were declared groundwater use restriction zones (GRZ) in 1997 and 1995, respectively.

GRZs have more rigorous waterwell-drilling controls aiming to reduce current, and prevent further, growth of groundwater abstraction. This is while still allowing: construction of more energy-efficient (replacement) wells and reallocation of groundwater resources to high-value uses by purchase and sealing of existing wells with construction of new wells at close-by locations within the same zone, even though water trading is not permitted under provincial water law. 'Sale' of excess surface water is also permitted in GRZs but with the relatively high costs of irrigation modernization, this is unlikely to be a great incentive to invest in water-saving measures.

The DGI is working towards a proactive groundwater management and protection programme to widen the base of stakeholder participation and foster shared appreciation of problems. The initial step identified to this end was to improve scientific understanding of aquifer behaviour. This has involved significant field work (e.g. intensification of groundwater level and salinity monitoring) to improve understanding of the hydrogeological structure and irrigation well abstraction/use patterns that will inform numerical modelling. Simulating various scenarios should allow evaluation of potential impacts, thus providing an improved basis for future conjunctive water use management.

Other land and water management measures to improve water-use efficiency and minimize the further mobilization of salinity instigated by DGI include:

- delivering surface water by lined canals/pipeline to increase efficiency, and reduce infiltration to uppermost saline aquifer to avoid water-table rise and increased downward leakage (Montecasero zone);
- providing additional water, from the surface water supply, to salinity affected areas by diverting excess riverflows;
- introducing drip irrigation techniques;
- backfilling or effectively sealing all disused, poorly-constructed and/or highly corroded waterwells (particularly to avoid transfer of brackish water in the Montecaseros);
- reducing rural electrical energy subsidies;

policing and reducing illegal pumping;
increasing riverbed recharge through works in the Mendoza riverbed; and
providing canal water to groundwater-only areas.

These measures have had varying impacts on the water balance of the Carrizal Aquifer, which are yet to be fully realized. Some remaining challenges include the following:

Groundwater rights have been granted in perpetuity and there is no mechanism to reduce entitlements to support more efficient use of water.
There is an absence of legal powers and market mechanisms that would enable the transfer of surface water entitlements to areas without access rights.
Surface water and groundwater have differential cost structures that apply to users, as groundwater users fully finance the associated infrastructure whereas surface water infrastructure has been either wholly or partly subsidized by the State.
Local water-user groups have been focused upon surface water issues, and there has been a reluctance to engage in groundwater management issues, which would require reorganization to better reflect the distribution of users[2].

Notwithstanding the above, the Carrizal Valley strategy appeared to be succeeding according to post-2007 monitoring data that suggest partial water-table recovery and groundwater salinity reduction.

3.3 Queensland – AUSTRALIA

Hafi (2002) highlighted the importance of taking a multiple-water-resource-system perspective in addressing issues of conjunctive use of groundwater and surface water in the Burdekin delta area, Queensland, Australia (Figure 6). Within this system, there is significant interaction between surface water and groundwater resources, and hence complementary policies have been formulated for surface water and groundwater management.

The Burdekin delta is a major sugar production district in Australia and overlies a shallow groundwater aquifer, which is hydrogeologically linked to environmentally sensitive wetlands, waterways, estuaries and to the Great Barrier Reef. In addition to irrigation supply, the aquifer also supplies potable water for three towns in the delta. The Burdekin River Delta aquifer consists of sedimentary deposits, up to 100 m below the surface. An important feature of the delta aquifer is that the sediments are not continuous laterally even over short distances. Discontinuity in impervious clay layers exposes the aquifer to infiltration of water from the surface and as a result the aquifer is generally considered unconfined. In terms of the hydrogeological settings defined in

[2] Overcoming this issue is exacerbated by the absence of a revenue base and the politicization of the user groups towards maintaining subsidized surface-water supplies.

Table 2 above, the Burdekin falls into the downstream alluvial delta category.

In the delta, surface water is pumped from the Burdekin River and diverted into canals to deliver to recharge pits and channel-intrusion areas and to irrigation farms (Figure 6). The channel system also delivers water to natural waterways, gullies and lagoons. The aquifer and the extensive canal, gully and lagoon system are collectively used as low-cost storage of diverted water and to capture a significant portion of the area's rainfall runoff. When the water diverted from the river is too turbid to be used in recharge pits or in excess of recharge capacities, it is made available as a supplementary irrigation supply. In normal years, rainfall recharge from outcrop areas and discharges from flooded rivers are sufficient to recharge the aquifer. However, after several successive years of drought, the aquifer has been depleted to near sea level mainly due to pumping for irrigation and continuous discharge to the sea.

A numerical model was used to identify optimal strategies to conjunctively manage groundwater and surface water resources to maximize their economic value. The model provided solutions relating to the optimal groundwater pumping levels required to manage the groundwater resource, such that the water table does not rise to levels that might cause waterlogging in some areas, and does not fall to a level that would permit seawater intrusion. This decision support tool has proved to be invaluable to water managers in the Burdekin River Delta. It provides information on optimal pumping quotas and the allocation of surface water resources. It further provides a basis for sustainable resource allocation, enabling decisions on the immediate use of supplies to meet short-term demand, and decisions supporting aquifer recharge for storage and future use.

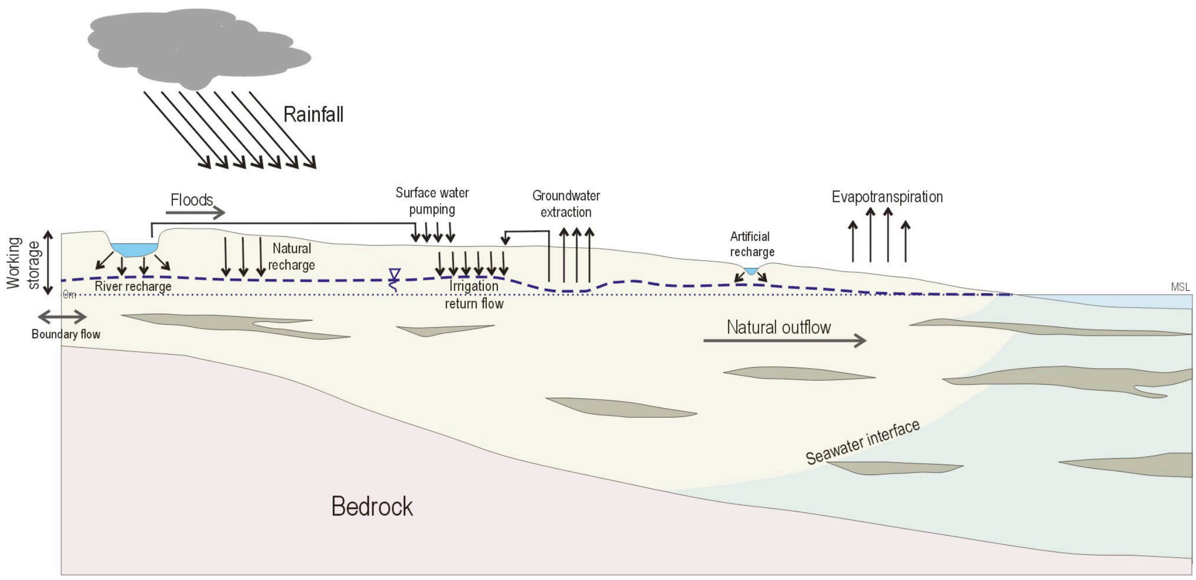


Figure 6 Water budget, Burdekin district, Australia (from McMahon, 2002)

The major conjunctive use regions in the Burdekin delta are managed through a separate act of the Queensland parliament. Two separate Water Boards were created covering different regions, which are controlled by a board comprising largely local water users. The board has substantial powers in the day-to-day operation of the scheme. The success of the scheme is characterized by strong and

clear local ‘ownership’, combined with significant technical support provided by government, and has the benefit of a hydrogeologically favourable region of high-transmissivity aquifers.

3.4 Indus Basin – PAKISTAN

Pakistan’s major groundwater resource is located in the irrigated areas of the Indus Basin. The hydrogeological setting can be classified as hyper-arid middle alluvial plain (

Table 2). Agriculture is the single largest sector of Pakistan's economy. Due to arid conditions in most parts of the country, the contribution of direct rainfall to the total crop water requirements is less than 15 percent. The huge gap between water availability and demand is bridged via exploitation of groundwater resources.

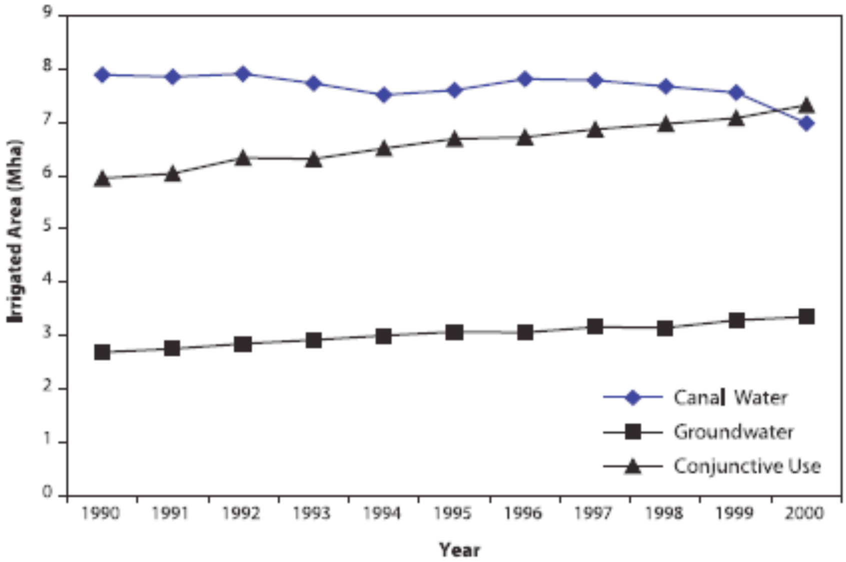


Figure 8: Increasing trend in conjunctive use, Punjab, Pakistan (taken from Qureshi *et al*, 2004)

Most groundwater exploitation in Pakistan occurs via conjunctive use with surface water. Irrigated agriculture using only groundwater is limited mainly to three situations:

- in areas not supplied by canal commands;
- in small systems outside the Indus Basin; and
- at the tail end of canal commands that have lost access to surface water through inequitable distribution of canal water supplies.

The most productive areas of the Indus Basin commonly incorporate conjunctive use of canal water and high to medium quality groundwater. Conjunctive use of groundwater and surface water allows farmers to cope with the unreliable surface-water supplies and to achieve more secure and predictable yields. However, there are adverse impacts of conjunctive use where poor-quality groundwater is used adding large amounts of salt in the root zone, and hence causing additional salinization problems to those arising from shallow water tables. In some areas, the salinity of the groundwater resource is such that there is full reliance upon canal deliveries to sustain irrigated agriculture. Even in areas where groundwater is deemed to be usable, the brackish nature of the resource commonly requires mixing with surface water prior to application to crops. However Qureshi *et al.* (2004) noted that farmers are not fully aware of the ratios required when mixing the two water types and hence negative consequences of irrigating with high salinity water have been observed.

The ratio of surface water and groundwater conjunctive use in irrigated agriculture identified in research undertaken by Murray-Rust and Vander Velde (1994) averaged 2:5 throughout the distributary canal command, resulting in an average irrigation-water electrical conductivity (EC) of

1 400 µS/cm. This value exceeds the current international standard that sets the upper limit for 'good' quality irrigation water at EC 700 µS/cm. To bring that average water-quality condition down to 1 000 µS/cm (still higher than the maximum value recommended by international standards), an average canal-tubewell water conjunctive use ratio of 3:4 would be required. Assuming no change in the total volume of irrigation water used in the command area, this means that the volume of canal water would have to be increased by more than 50 percent and the volume of pumped groundwater reduced by more than 20 percent of current volumes.

In addition to the technical issues, institutional challenges are also significant. Murray-Rust and Vander Velde (1994) highlight that, to halt the declining trend in sustainability of Pakistan's irrigated agriculture, "Pakistan's public agencies and supporting research institutions must begin shedding this 'historical baggage', reorganize internally and establish functional, working linkages with one another".

3.5 Other examples

Sahuquillo (2005) discusses a number of examples under the theme of alternate use of groundwater and surface water for irrigation in a more general discussion of conjunctive use. These examples are from the Mediterranean Basins of Spain and the Central valley of California, United States of America (USA).

In the Spanish basin examples, Sahuquillo (2005) reports on the evolution of conjunctive use as a process associated with the expanding irrigation industry during wet years via surface water diversions. As groundwater resources were identified through the region, more and more groundwater abstraction was incorporated into the system. In response to an expansion in the irrigated area, more intense use of surface water during wet years increased, leading to substantial increases in overall use. These examples demonstrate a bottom-up approach that was proposed and implemented by the irrigators, which have now been incorporated into legally sanctioned schemes.

Sahuquillo (2005) discusses in more detail the status of the Mijares Basin, near Valencia, Spain. The basin is characterized by large surface water reservoirs situated over a karstic limestone aquifer, with resulting high leakage rates to groundwater. In addition, the Mijares River also leaks and recharges the local alluvial water-table aquifer. Surface water or groundwater is used as the water source depending on water availability, both in stream and in storage. The beneficial aspect of the relationship between surface water and aquifer is that, whenever more surface water is available – which is hence used by irrigators –, recharge rates to the groundwater system are higher. This provides a natural counter-cyclical process, where the groundwater resource is recharged during periods of low groundwater demand.

Bredehoeft (2011) provides some examples of conjunctive use operation in the western USA as part of a more general discussion of conjunctive use. The examples highlight the situation where surface water was generally first developed and used to its maximum to undertake irrigation – usually fully developed by the early 1900s. Bredehoeft points out that a large number of these river valleys contained alluvial deposits whose groundwater systems were well connected to the rivers. As surface water was fully appropriated, and as knowledge of the groundwater systems grew,

groundwater became the new water source, and development followed in a generally unregulated fashion. Institutions to manage abstraction have evolved over time. They have, however, generally favoured prior rights in water and required the newer water users, that is, the groundwater users, to provide 'new' water to offset their pumping impacts. Consideration of opportunities to solve these challenges does not appear to have explored conjunctive resource management.

Pulido-Velazquez *et al.* (2004) and, to a certain extent, Sahuquillo (2005) discuss an interesting adjunct to the idea of conjunctive use. Both sets of authors provide examples of conjunctive use occurrences, where the surface water resource is used to artificially recharge the groundwater resource. Pulido-Velazquez *et al.* (2004) discuss the situation in Southern California, though associated with water supply projects for metropolitan areas rather than irrigation, and Sahuquillo discusses examples associated with treated wastewater near Tel Aviv, Israel, and Barcelona, Spain. Whilst not directly relevant to irrigation supplies, they do demonstrate a further type of conjunctive management that could be implemented elsewhere, presumably subject to cost.

These examples highlight a common history and common challenges. In nearly all cases where conjunctive use is being practiced (either spontaneously or in a planned manner), surface water was the dominant historical water source. Either through expansion, technology uplift, new knowledge or deteriorating water access/quality there were moves towards incorporating groundwater into the water management system. This was done either within a regulatory environment (with varying degrees of compliance) or spontaneously by individuals. The development of both water sources brings into juxtaposition the inherent difference between surface water and groundwater. Surface water is predominantly a State-owned or managed "good" that in most cases is heavily subsidized via direct infrastructure spending, as a part of national agricultural or food security policy. Groundwater, on the other hand, is rarely State-owned and managed and does not usually attract the same level of subsidy. In other words, the management of groundwater and surface water are commonly underpinned by different philosophies, differences that arguably are a significant impediment to progressing conjunctive management.

The main impediments to planned conjunctive use identified by Foster *et al.* (2010), as summarized from their work on examining a number of global examples of conjunctive use, are:

> the often disconnected responsibilities for water management between surface water and groundwater departments at various levels of government, which usually results in a failure to understand the integrative benefits of holistic resource management;
> the lack of information regarding conjunctive use management that can be used to influence and educate both politicians and the general public about conjunctive use benefits; and
> an inadequate knowledge of the degree to which privately-driven groundwater use is practiced in irrigation commands, its benefits and its risks.

4. Scope for securing social and environmental benefits through conjunctive use schemes

It is often instructive to consider where a particular approach has succeeded compared with examples where sub-optimal outcomes have been apparent. In order to gain such insight, a common understanding as to what success means within the context of conjunctive management is required.

The thread of this paper, based on others' work (primarily that of Foster and others) is that planned conjunctive use management should be a clear objective wherever both surface and groundwater resources are available. As alluded to earlier, whilst there are few examples that demonstrate effective implementation of planned conjunctive use management, spontaneous conjunctive use is common. The apparent widespread evidence of this spontaneous conjunctive use suggests that substantial financial benefits are being realized by irrigators, otherwise the practice would not prevail.

Two end-members of a possible continuum between successful attempts to retrofit conjunctive use management (which by its very nature must be planned) and areas where it is not possible to retrofit are proposed as Utter Pradesh in India and the South Platte Valley in Colorado, USA, each of which is discussed below.

In Utter Pradesh, a planned approach was implemented at the regional scale aimed at effecting changes to the water supply/demand balance by considering the nature of the complete water cycle for the area and how this behaved spatially and temporally. A series of actions were then undertaken to optimize the existing infrastructure so as to enable a larger amount of water to be accessed in a more efficient manner. It seems there was little in the way of State-sponsored investment and no apparent changes to management and/or regulation levels. However, local ownership was focused on increasing the total water availability. The benefits of these actions have been widely reported.

Conversely, within the South Platte River Valley of Colorado, the focus upon conjunctive management has been to apply existing regulations around water rights in groundwater abstraction and use, rather than considering appropriate reforms that may assist in delivering broader and longer-term water management outcomes. As Bredehoeft said (as reported above): "Effective conjunctive management can probably only be accomplished by an approach that integrates the groundwater and surface water into a single institutional framework; they must be managed together to be efficient. Current institutions based upon the present application of the rules of prior appropriation make conjunctive management not practical." This is because the existing surface-water rights are strongly maintained and enforced by the relevant water authorities and, consequently, groundwater is not able to be used in an unencumbered conjunctive-use sense.

If these two high-level summaries reflect the broader experience related to conjunctive use management then the key to successful implementation is complex and probably reliant on a mix of institutional, social, technical and economic factors that vary at the local to sovereign level.

The social, technical and economic factors require consideration within the local context, as they are critical to developing the optimum management arrangements. However, the optimum approach

may prove to be purely theoretical, if implementation is inhibited by existing institutional or policy structures. This specifically applies to the legal 'ownership' of water rights, the ability of local bodies or water user associations to make day-to-day decisions and the ability to undertake effective planning for conjunctive use.

It is clear that there needs to be economic incentives to justify the adoption of conjunctive use management at both (or either of) the sovereign or individual level, independent of whether there are strong market drivers operating. As discussed briefly in previous sections of this paper, it appears that economic gain is made – where it has been assessed and reported – as a result of the adoption of conjunctive use management. This has usually been at the farm-gate level in the form of reduced costs and increased income, however economic returns may also be achieved at the sovereign level through more efficient use of the available water resource, lower subsidies to achieve the same production and increased levels of production leading to more regional development opportunities from post-farm gate multipliers. Further work to demonstrate the sovereign-level economic gains is probably warranted as part of a programme to encourage governments to commit to the institutional and policy reforms necessary to achieve adoption of planned conjunctive management at an irrigation-command scale. For effective management, regulatory arrangements are required to include access entitlements and powers to place restrictions on the timing and volume of water abstraction.

A number of researchers have assessed and confirmed the gains to be made from conjunctive use management (for instance, see Shah *et al.*, 2006). Where economic gains have been assessed in investigations and research studies, all show positive results. This knowledge has become a major piece of evidence used to promote the implementation of conjunctive management in recent years. However, the extent of the analysis of socio-economic benefits at the irrigation-command level is limited and mainly held in unpublished reports. It is rare to see detailed analyses of the benefits and costs of conjunctive use; rather the data shows the incremental economic benefits when conjunctive use management is retrofitted to unplanned irrigation commands. In particular, it is rare to see an analysis of benefit and cost associated with planned conjunctive management, and even rarer to see a discussion of the policy and institutional approaches supporting planned conjunctive use. Very few researchers or commentators provide detail on what policies need to be put in place. It is the authors' view that this is a major impediment to the 'socialisation' of the issue across governments.

5. Governance tools that promote the adoption of conjunctive use

A range of management models exist across numerous irrigation developments around the world. Most surface-water-based delivery infrastructure tends to be in public ownership, while most groundwater relate infrastructure is farm-based and hence tends to be privately owned. The different ownership arrangements between groundwater and surface water tend to correlate strongly with the degree of commitment from governments towards management of the resource. This situation is depicted in Table 6.

Table 6: Varying ownership models and degree of management for groundwater and surface water based irrigation commands.

		Public Ownership of Infrastructure (Government/State-Owned)	Part Public and Part Private Ownership of Infrastructure	Private Ownership of Infrastructure
Degree of management	Highly Managed	Common – usually surface water based	Common	Rare
	Lightly Managed	Not common	Very common	Not common
	No Management	Rare	Common	Common – usually groundwater based

Evidence of the differential attributes presented within Table 6 is apparent when considering specific examples around the world, with such differences being potentially 'cultural' in nature. For example, in most parts of India, private ownership of groundwater wells prevails, and there is minimal groundwater management, with some notable exceptions (IWMI, 2006). However in circumstances where there is communal ownership of groundwater wells, a stronger management framework is likely, albeit still very locally based.

Well-planned conjunctive use is theoretically easier to achieve with public ownership. Conversely, in a private-ownership model, stronger regulations and/or sanctions, or appropriate market mechanisms are normally required to support a transition to effective conjunctive management. However the objective should always be tailored towards providing well-planned conjunctive use models irrespective of the public/private ownership model, and whether there are centrally-regulated or market-driven environments.

One obvious market mechanism that should be considered within a planned conjunctive management regime is water trading, which requires a water allocation framework that sets limits on entitlements to sustainable levels of take. When the allocation framework has fully committed these entitlements, a trading regime – either explicitly or implicitly implemented – is an effective method to allow for redistribution of water in response to market forces. In a fully-integrated conjunctive management model, such trading regimes may enable groundwater to surface water trade (and *vice versa*), with associated rules necessarily being highly cognisant of the amount and timing of the hydraulic interaction and other attributes of the different entitlements.

Table 7 provides a simple outline of the types of management approaches and of attempts to classify them based on the degree of connection between surface water and groundwater and on the degree of regulation of water resources by the State. The table acknowledges the continuum in (effective) regulation of the water resource and sets out broad approaches.

Table 7: Possible management approaches to achieve planned conjunctive use for varying management models and degree of hydraulic connection between groundwater and surface water.

Degree of Connection	Highly Regulated	Lightly Regulated	Free Market
Highly connected	Relatively simple management rules	General management rules necessary	Low level of management may be required – potential for optimal resource use
Moderately connected	Specific management rules required	Specific management rules required	Specific management rules required
No practical connection	Need for integrated management is more important	More involved management necessary	Complex management required – some regulation necessary

5.1 Required institutional structures for effective conjunctive use management

Conjunctive use management is not constrained mostly by a lack of technical understanding (though this is an important constraint), but rather by ineffective and incompatible institutional structures, with separate management arrangements, almost always established and operated by different institutions. As well, water resources at the sovereign level are often managed by a dedicated agency, whilst irrigation commands are often managed by agricultural agencies or dedicated irrigation-command authorities. Overall water resource policy may be set at a jurisdictional scale with the irrigation sector required to operate under the authority of a regulatory agency. This results in a complex mosaic of planning and decision pathways that are not easily overcome in the pursuit of a planned conjunctive management model.

Foster and Steenbergen (2011) acknowledge that: "In many alluvial systems, the authority and capacity for water-resources management are mainly retained in surface-water-oriented agencies, because of the historical relationship with the development of irrigated agriculture (from impounded reservoirs or river intakes and major irrigation canals). This has led to little interest in complementary and conjunctive groundwater management. Some significant reform of this situation is essential – such as strengthening the groundwater-resource management function and/or creating an overarching and authoritative 'apex' agency''. Similarly Shah *et al.* (2006) recognize that: "Water resources are typically managed by irrigation departments and groundwater departments. There is rarely any coordination between these ...".

Foster *et al.* (2010) also emphasize that: "The promotion of improved conjunctive use and management of groundwater and surface water resources will often require significant strengthening (or some reform) of the institutional arrangements for water resource administration, enhanced coordination among the usually split irrigation, surface water and groundwater management agencies, and gradual institutional reform learning from carefully monitored pilot projects. Water organizations and agencies often tend to 'mirror' historical water-supply development realities and tend to perpetuate the *status quo* and find it difficult to grasp conjunctive use opportunities. There is often considerable rigidity, and initial resistance to change." Add to this a higher-level need to align water resources and agricultural strategy, at both the sovereign and sub-regional irrigation-command level, and the enormity of the task becomes apparent.

Bredehoeft (2011) emphasizes that effective management of conjunctive use "requires integrated institutions that can plan and sustain the management of the system for long periods". This is because it typically "takes more than a decade for significant changes in groundwater pumping ... to have their full impact on the river" (as seen in the USA case he studied). Bredehoeft also stresses that, in much of the USA, the water management legal system based on prior appropriation fundamentally works against conjunctive management: "Effective conjunctive management can probably only be accomplished by an approach that integrates the groundwater and surface water into a single institutional framework; they must be managed together to be efficient. Current institutions based upon the present application of the rules of prior appropriation make conjunctive management not practical." Conjunctive use management will require major organizational change in water agencies. Furthermore reformed institutions need structures that can operate at the multiple scales with which groundwater, especially, requires.

A recent report for the World Bank (Garduño *et al.*, 2011) discussed that "The promotion of more planned and integrated conjunctive use has to overcome significant socio-economic impediments through institutional reforms, public investments, and practical measures, including: (a) the introduction of a new overarching government agency for water resources, because existing agencies tended to rigidly follow historical sectoral boundaries and thus tend to perpetuate separation rather than the integration needed for conjunctive use; (b) gradual institutional reform learning from carefully monitored pilot projects; and (c) a long-term campaign to educate farmers through water user associations on the benefits of conjunctive use of both canal water and groundwater, crop diversification, and land micro-management according to prevailing hydrogeologic conditions." These commentators reflect a view that institutional strengthening is probably the most important challenge to conjunctive use management, especially in already developed irrigation systems where a more optimized management approach needs to be retrofitted.

5.2 Optimum conjunctive management and what is meant by conjunctive use planning

Important factors to be considered in the planning process to optimize the use of groundwater and surface water are the fundamental differences between the two water sources in terms of: availability; cost, both capital and operating; and energy requirements (and hence CO_2 impacts). These three factors need to be considered individually and collectively to develop a well-planned conjunctive-use irrigation system. Of these, the different availability (as a volume) and timing between groundwater and surface water is already recognized and positively utilized in optimisation planning.

Cost differences – as usually seen by farmers – between groundwater and surface water are a key factor to be considered, with subsidies common for electricity supplies (see, for example, Shah *et al.*, 2006) impacting upon farmers behaviours (i.e. choices between surface and groundwater) and hence leading to outcomes that are not consistent with water planning objectives. In addition, the net environmental outcomes resulting from a management strategy are not yet considered in most planning frameworks, such as the CO_2 impact of different options. Many authors (for example Piludo-Velazquez *et al.*, 2006) have produced economic optimization approaches. These tend to rely

on assuming that there is a water-trading regime in place that allows or encourages the redistribution of total water resources to the greatest economic good. In practice surface water to groundwater (and *vice versa*) trading regimes rarely operate across irrigation-command areas worldwide. However, such a trading approach should be encouraged as part of effective conjunctive management, noting that there are likely to be significant challenges in establishing rules that take into account the different nature of the resources. All the above factors must ultimately aim to produce the maximum crop yield per cubic meter of water used.

Part 3: Prospects

6. Prospects for slowing or reversing trends through 'governance'

The broader topic to which this paper contributes is related to groundwater governance. However, within the context of conjunctive use management, it is important to consider water governance globally, that is, governance for both surface water and groundwater. Good governance principles associated with groundwater alone still apply, but they must be made to fit a broader governance paradigm – so-called Integrated Water Resource Management (IWRM).

General water governance principles cover a number of main areas – authority, accountability, transparency, stakeholder participation and institutional integration. Authority relates to the policy and statutory powers vested in the government or delegated to an agency to administer and regulate on behalf of the government. The associated 'authority' becomes the decision-maker who must be held accountable for operationalizing policy and legislative instruments. Such an authority must be accountable for its decisions, with appropriate mechanisms in place, supportive of natural justice by enabling appeals against decisions to be independently reviewed.

As a third element, transparency is required to demystify the decision-making process, support stakeholder confidence in the management process and provide the grounds for any appeal. Participation is required to ensure that there is ownership of the process by all stakeholders; this goes a long way to achieving planned outcomes. Finally, integration (both institutional and technical) is required to ensure that all aspects of water tenure are subject to a single basic water resource regime. Water is a single resource and should be managed accordingly.

6.1 Governance approaches

It is clear that optimum water-resource use will be significantly advanced through planned management of conjunctive use in irrigation commands worldwide. There are a number of areas where the governance model is crucial to the adoption of this planned management approach. However, it is useful to note that there is no single governance model that can be applied universally; rather elements of different approaches may need to be chosen depending on the specific circumstances for each case.

Effective governance arrangements to underpin a conjunctive management strategy are deemed to be the most significant challenge. Danton and Marr (2007) in a discussion of the governance arrangements associated with the Uttar Pradesh conjunctive use example, make the point that "multi-faceted governance arrangements are necessary for successful management of smallholder surface water irrigation systems. In managing conjunctive use ... these arrangements become more complex.... The greater complexity in management arises from the need for coordinated management of the two resources through greater participation and networking of stakeholders at each stage of water allocation, use and management." Further, Livingston (2005; as referenced in Danton and Marr, 2007) subdivides water governance models for water supply systems into three types: bureaucracy, community and market. Governance approaches may favour one model, but will ultimately include elements of all three.

Garduño and Foster (2010) listed a number of challenges when considering the governance of conjunctive use management. They reported that: "Serious impediments have to be overcome to realize such water resource management policies. They are primarily institutional in character, given that the structure of provincial government organizations often simply mirrors current water-use realities and tends to perpetuate the *status quo*, rather than offering a platform for the promotion of conjunctive management."

In summary, the governance model needs to address four areas of endeavour: legislative, organisational, capacity and socio-political. In many countries, the organizational aspect may require the most significant changes to be made.

6.1.1 Institutional strengthening

Institutions that manage water, at both the national and regional scale, need to be strengthened to remove impediments. This requires the adoption of frameworks that promote IWRM where surface water and groundwater functions operate collectively towards a single overarching objective, and the function of water and agriculture ministries are also aligned for this purpose. Institutions need to be clear on who operates and manages irrigation commands; arrangements that may be inclusive of either the public or private sphere, or a combination of both.

The resolution of chain of command issues across various levels of government also needs to be reviewed. That is, each level of government must understand its role in implementing national water resource policy and be effective in enacting that role. Counter-activities at any level must be confronted and remedies provided. Institutions need to have a strong compliance culture to ensure that outcomes are achieved.

6.1.2 Policy and legislation

In many instances, there is a need to understand and review the current approaches to allocating rights in water, and the form and attributes of those rights. In many situations, policies and regulations may be poorly formulated and hence not operating efficiently to achieve the intended outcomes. Effective water allocation planning is paramount. Such planning needs to be supported by strong national policy and to occur within a framework that ensures sustainable levels of take and

use of the resource. This requires significant technical input, especially within the context of the need to assess the available consumptive pool.

Conjunctive use management relies on water policies and regulations that are efficient at promoting movement of access between the two resources when required and appropriate. Legal and market powers and mechanisms must be aligned to achieve this goal.

6.1.3 Planning

By its very nature, planned conjunctive use requires a strong management platform. There is a need to clearly define objectives, outcomes, activities and performance measurement and compliance arrangements. Such plans should be based around water allocation mechanisms and have regard to the technical understanding of the total consumptive water available.

Implementation planning requires definition of investment requirements and decisions about who will make those investments, and who will ultimately pay. Ideally, planning should incorporate the triple-bottom-line notions of achieving environmental, economic and social objectives.

Conjunctive use management also requires consideration of land use policy changes so that groundwater protection outcomes can be achieved. This is not a usual set of policy decisions in most developing and developed countries and may not only require considerable input, but also political support.

6.1.4 Market and pricing approaches

Surface water and groundwater always have differential cost structures that apply to users. In centralized government systems, these cost structures may be heavily subsidized as a result of related policy decisions (for instance, those for food and energy) and there may be unwanted outcomes as a result; usually, these relate to poor water use efficiency outcomes. In general, groundwater users fully finance their associated infrastructure whereas surface water infrastructure has been either wholly or partly subsidized by the State. The different ownership models contribute to differential cost impacts for irrigators, leading to decisions that are inconsistent with optimized planning objectives. Conjunctive management needs to understand and remove these impediments. State-sponsored groundwater development is an area where investment may be required.

There are also be differences in economic approaches at the macro and micro scale, and any activity to enhance the water market needs to acknowledge the two different scales of benefits. This is also true where economic incentives are implemented.

6.1.5 On-the-ground implementation

Planned conjunctive use management will benefit strongly from, and possibly require, strong ownership by the irrigated farming sector. This can be achieved by building strong local water user

groups through targeted education and enabling actions. In the past, communities have been focused upon single issues (either surface water or groundwater) and there has been a reluctance to engage in management issues associated with the other side of the resource picture that would require reorganization to better reflect the distribution of users. Overcoming this issue is exacerbated by a number of factors including the absence of a revenue base for cost recovery and the politicization of the user groups towards maintaining subsidized surface water supplies. There needs to be a participatory culture of education, demonstration and capacity building between governments and the irrigation farming community and its key stakeholders.

6.1.6 Knowledge generation

To facilitate conjunctive use management, knowledge is required in two key areas – technical understanding of the spatial and temporal distribution of the total consumptive available water and support for planning through the capability to provide future impact scenarios. The latter is generally in the form of a complex numerical model of aquifer-river basin performance. Conjunctive use management also requires the establishment or improvement of monitoring programmes so that the quantity and quality impacts of the use of surface water on groundwater and *vice versa* can be demonstrated, and so that the beneficial impacts of water management actions can be seen by all stakeholders.

6.2 Use of financial and market-based instruments to promote planned conjunctive use

Financial and market-based instruments (FMBI) are a range of financial and economic measures that can be used to encourage specific actions and trends. In the context of water resource planning, FMBI can consist in direct financial incentives (e.g. taxation reduction, subsidies to lower electricity prices) or disincentives (e.g. taxation increases) or alternatively indirect tradeoffs or offsets (e.g. pollution reduction schemes) and the introduction of water trading.

Some countries have favoured a regulatory approach to bring about various water resource outcomes, while other countries have tended to favour economic instruments, in the belief that clear financial signals are a strong lever to active policy objectives. In the case of conjunctive use, the authors are of the view that in many countries subsidies that distort the true cost of water delivery (surface water and groundwater) bias irrigator behaviours and hence retard the potential for planned conjunctive use to contribute to optimal water use outcomes.

Conversely other FMBI (i.e. those not aligned with subsidies) can be a very powerful tool to encourage the adoption of optimal conjunctive use. The range of options tends to be very location- and culture-specific. Nonetheless schemes that provide both financial incentives (e.g. through taxation decreases), when a defined minimum volume of water is used conjunctively, and indirect economic offsets (e.g. for salinity control) are considered the most effective. These should generally be used to 'kick start' planned conjunctive use and should not be seen as permanent measures.

The introduction of clearly defined water rights, the application of well defined caps (i.e. maximum limits of use of groundwater and surface water) and the introduction of a water trading regime can operate to strongly facilitate more efficient total water use. Surface-water trading regimes currently operate in many countries, however groundwater-trading regimes are not so common. Surface water to groundwater (and *vice versa*) trading regimes are rare. Nonetheless water trading can represent a strong market instrument to encourage conjunctive use, if it is managed appropriately. There are, however, few examples in the world where this has occurred. This is especially an issue where market mechanisms are not designed to account for environmental impacts (e.g. salinity effects).

FMBIs are not readily recognizable where governments exercise centralized control as opposed to a market-based approach. However, in such centralized governance approaches, positive benefit-cost outcomes through similar initiatives as FMBIs can still be achieved in terms of measures of 'national good', that is, national gross production from irrigated agriculture, poverty alleviation, etc. The issue here is about applying the most appropriate reward and compliance signals to the water/irrigated agriculture sector.

This discussion also indicates that water management policy – and its role in planned conjunctive use – is part of a larger policy position by governments that involves national food policy, poverty alleviation, economic growth, sustainability, climate change and energy considerations. Good governance is more likely to ensue once the impact on national water use policy of policy decisions (including subsidies) in these related areas is considered.

6.3 A suggested set of conjunctive use principles for consideration within a governance approach

The following is a suggested set of principles for the implementation of conjunctive use management within existing irrigation commands, where infrastructure and historical governance arrangements are in place:

- Planning should be undertaken with full and detailed knowledge of the characteristics of both the surface water and groundwater systems, of existing system operations and of the demands of the cropping systems.
- Goals should be established that are intended to optimize the water supply/demand balance, irrespective of existing institutional, governance and regulatory models.
- Revised institutional arrangements underpinning the new conjunctive management model must be supported with a strong policy and legislative base.
- The combined surface water/groundwater system and their use should be managed so as to optimize net economic, social and environmental benefits, taking into account national energy, food security, population and poverty reduction, sustainability and climate change policies and programs.
- Stakeholder participation should be encouraged.

From an operational point of view, some key guidelines to implementing conjunctive management include:

- a technically robust understanding of stream-catchment-aquifer interactions;

a water balance that is inclusive of connectivity between the surface and groundwater systems;

technical assessment techniques commensurate with the understanding of the hydrological system and with explicit recognition as to the limitations to the validity and applicability of information;

a strategic monitoring programme for the catchment, including the alignment of groundwater and surface water monitoring[3].

In summary, conjunctive use planning is the structured water-planning process whereby the different characteristics (technical, economic, social and institutional) of groundwater and surface water are compared and weighed against each other so that the optimum use of the two water sources is achieved. The fact that this rarely occurs throughout the world is testament to the entrenched water institutional structures and the very poor understanding of fundamental technical processes.

7. Conclusions

a) There is a range of settings within which conjunctive use management can occur, and there do not appear to be any situation where conjunctive use management should not be practiced.

b) Planned conjunctive use management is far better than spontaneous conjunctive use in terms of deriving a better set of outcomes from the point of view of the resource, of national good and economic return.

c) Most development has already occurred and no new 'greenfield' irrigation developments are likely at a significant scale, thus most implementation of conjunctive use management will be by retrofitting management arrangements to already existing systems.

d) There are major economic and social reasons to encourage planned conjunctive use, an opportunity the world cannot afford to continue ignoring.

e) Poverty reduction in irrigation areas is closely linked to water supply efficiency and hence to conjunctive use management.

f) Institutional, economic, social and technical challenges will need to be addressed, probably in that order, at the sovereign scale.

g) The regulatory settings for water management for different sovereign States will be the most important setting for management approaches. Any institutional strengthening will need to be supported by strong policy and possible legislative changes.

h) Conjunctive use management will be linked to sovereign policies related to energy, climate change adaption and to food security and hence a broader governmental approach will need to occur.

[3] Monitoring regimes should recognize the differences between assessment monitoring and management monitoring. Management monitoring refers to the monitoring of management rules and processes whilst assessment monitoring refers to monitoring of the technical or scientific aspects of stream-aquifer interactions (Fullagar, 2004).

i) An important part of planned conjunctive use is the identification of the true total cost of water resources and the separate cost to individual users (for example, electricity subsidies are very common), which can greatly differ.
j) The degree of connectivity of surface water and groundwater is an important technical consideration, but not one that will greatly influence whether conjunctive use management is successful.
k) Institutional strengthening around groundwater management and a fully integrated water agency will be a major challenge in most areas.
l) A minimum standard for conjunctive use management is the presence of some form of institutional arrangement related to groundwater management, which addresses issues such as sustainability via some form of regulation.
m) Public education and supporting technical assessments is an important part of conjunctive use management.
n) Approaches that generate the greatest degree of flexibility in water management are to be encouraged.

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