

Sustainable Groundwater Management Contributions to Policy Promotion

Strategic Overview Series Number 2

Conjunctive Use of Groundwater and Surface Water from spontaneous coping strategy to adaptive resource management

2010

Authors: Stephen Foster, Frank van Steenberg, Javier Zuleta* and Héctor Garduño
(* World Bank - South Asia Region)

The aim of this overview is to provide a strategic guide to current practices of conjunctive use of groundwater and surface water resources for both irrigated agriculture and urban water-supply in the developing world - and the great potential that planned conjunctive use has as an adaptation strategy to accelerated climate change. It is primarily (but not exclusively) of relevance to larger alluvial plains, which often possess major rivers and important aquifers with large storage reserves in close juxtaposition - although conjunctive use potential can arise in a wider range of hydrogeological settings. Emphasis is put on analysis of the technical, institutional, social and economic impediments that often exist when attempting to promote more rational and efficient conjunctive use, and on approaches to overcoming them.



CONTENTS

	Page
SCOPE OF CONJUNCTIVE USE	3
Adopting a Pragmatic Definition	3
Significance for the Developing World	3
CONJUNCTIVE USE FOR URBAN WATER-SUPPLY	6
Strategies to Improve Water-Service Security	6
Overcoming the Main Impediments to Planned Conjunctive Use	7
PANORAMA IN MAJOR IRRIGATION CANAL COMMANDS	12
Spontaneous Sub-Optimal Conjunctive Use by Farmers	12
Groundwater Resource Sustainability Limits	13
Advantages of Better Planned Conjunctive Use	18
Overcoming the Main Impediments to Planned Conjunctive Use	22
CONCLUDING REMARKS	24
Technical Foundation	24
Institutional Requirements	24
Acknowledgements	25
Further Reading	26
BOX A Lucknow - India	8
BOX B Lima - Peru	10
BOX C Mendoza - Argentina	16
BOX D Uttar Pradesh - India	20

SCOPE OF CONJUNCTIVE USE

Adopting a Pragmatic Definition

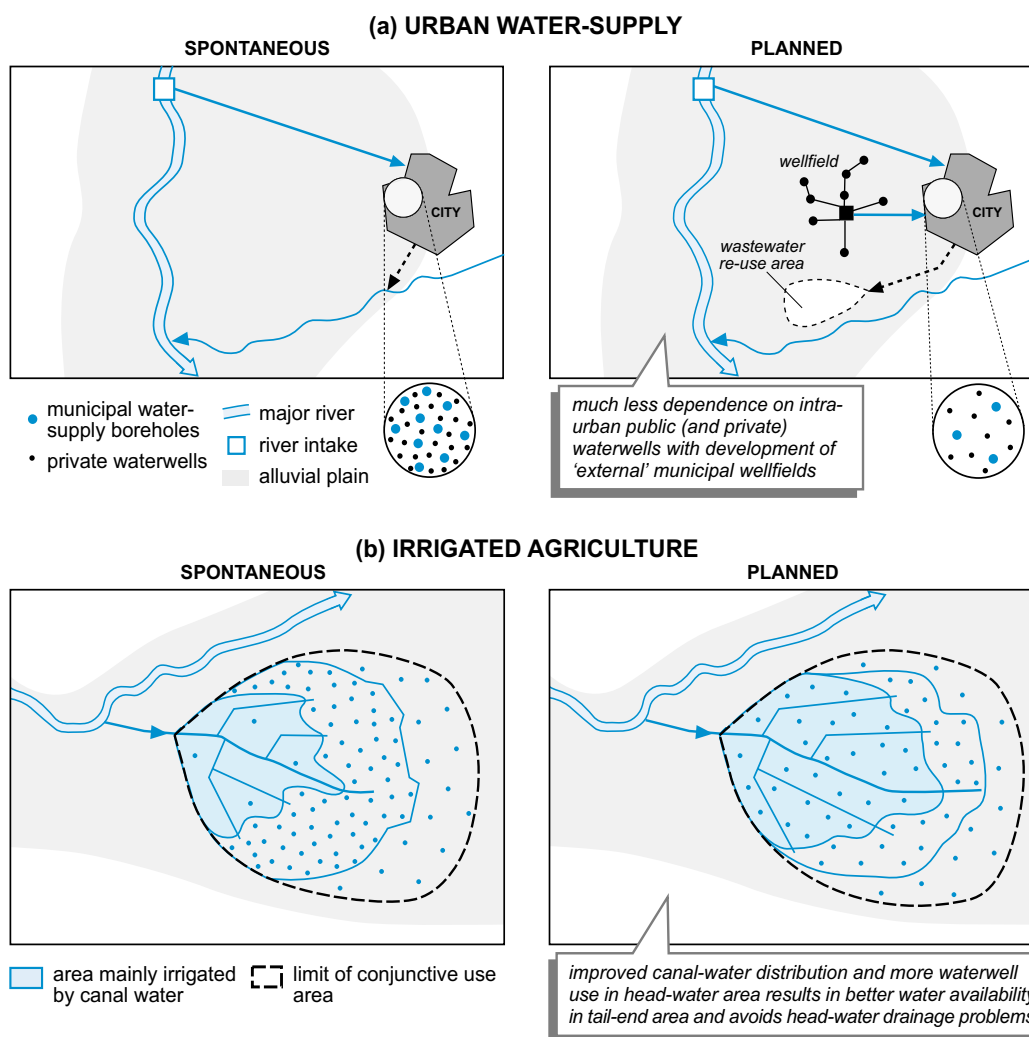
- There is no rigorous definition for the ‘conjunctive use’ of groundwater and surface water resources. But for the purpose of this overview it is proposed to consider only situations where *both* types of source are developed (or co-exist and can be developed) to supply a given urban area or irrigation canal-command – although not necessarily using both sources continuously over time nor providing each individual water user from both sources.
- A key characteristic of conjunctive use is that it usually aims to use the very large natural groundwater storage associated with most aquifers to ‘buffer’ water-supply availability against the high flow variability and drought propensity of many surface watercourses – making it especially important for the mitigation of climate changes impacts, which in many scenarios will lead to increased intensity of droughts. A second important feature is that conjunctive use is often the best way to confront some of the serious problems of groundwater salinization and soil waterlogging on alluvial plains.
- Adopting this rather ‘narrow definition’ excludes consideration of :
 - the artificial recharge of aquifers with surface run-off or by rain-water harvesting (without direct supply from the surface water source)
 - the use of groundwater pumping to support river baseflows (without direct supply from waterwells).

It is recognized that some authors include these techniques within the scope of ‘conjunctive use’, and it is not the intention here to suggest that they are not of the highest relevance for water resources management. But to maintain a sharp focus in this review on direct water-supply investments in the developing world, it was preferred not to consider them in detail here.

Significance for the Developing World

- In urban water-supply some form of conjunctive use of groundwater and surface water sources is commonplace – but in rapidly-expanding cities it is often unplanned and not recognized as such (Figure 1a), nor optimized in terms of the complementary hydrological characteristics of the two sources. It arises both in cities originally supplied from :
 - ‘traditional’ groundwater sources (springheads or waterwells) at the urban nucleus
 - immediately neighboring surface watercourses
 either one of which subsequently became insufficient with urban growth, at which time additional (more costly) surface water or groundwater sources respectively were introduced. However, there is no comprehensive global database of urban water-supply sources from which to abstract reliable statistics.
- Spontaneous conjunctive use for agricultural irrigation occurs widely and increasingly on alluvial plains (Figure 1b), through the private initiative of farmers in response to a combination of declining service levels in main irrigation canals and growing irrigation demand. In most large

Figure 1 : Typical schemes of conjunctive use of groundwater and surface-water resources for (a) urban water-supply and (b) irrigated agriculture with evolution from unplanned or spontaneous occurrence to planned development



irrigation canal commands there is a ‘conjunctive reality’ that is often hardly acknowledged – not being reported as such in the UN-FAO Aquastat Database because national information often only indicates the ‘initial’ or ‘dominant’ water source in any given irrigation (or irrigated) area.

- In effect conjunctive use of groundwater and surface water sources, in some form or other and with varying degrees of effectiveness, is capable of achieving :
 - much greater water-supply security – by taking advantage of natural groundwater storage in aquifers
 - larger net water-supply yield – than would generally be possible using only one source alone
 - better timing of irrigation-water delivery – since groundwater can be rapidly deployed to compensate for any shortfall in canal-water availability at critical times in the crop-growth cycle
 - reduced environmental impact – by counteracting land waterlogging and salinization, and excessive riverflow depletion or aquifer overexploitation.

The implication is that a different approach to water resource development is required to achieve these benefits, which will often involve the mobilisation of both public and private capital (Table 1).

- To achieve the maximum water-user benefits whilst minimizing the associated environmental impacts, it will be necessary to manage the conjunctive development of water resources such that :
 - a balance is created between local recharge and groundwater use
 - the impact of surface-water offtake does not extend into the low riverflow period
 - the impact of waterwell abstraction is largely delayed until high riverflow periods.
 As such the degree of hydraulic connectivity of alluvial aquifers with the overlying surface water-courses and the volume of surface water ‘delivered’ to a given area are important considerations.

- It is especially important to register that the ‘conjunctive management approach’ will in many areas be critical for the definition of realistic strategies for water-resource adaptation to the impacts of accelerated climate change – in which the frequency and severity of surface water droughts increase and are coupled with growing water demands associated with higher ambient temperatures.

- Examples of catchment-scale integrated and optimized multi-sector water resources management, which embrace everything from flood protection to wastewater reuse (and often first deploy fresh-water resources for urban use and then reuse them for agricultural irrigation to increase ‘water productivity’), are also not presented here. Such approaches, which have been developed in areas of severe water scarcity (such as California, Israel and South Australia) have (necessarily) to be based on a level of water resources administration and technological investment distant from the present reality of most of the developing world. But it is recognized that within such schemes there are often excellent examples of ‘conjunctive use’, and the spontaneous and unplanned wastewater reuse is a widespread practice in the developing world which requires less capitalised and administratively intensive approaches to address (see **GW•MATE Briefing Note No. 12 on Wastewater as Groundwater Recharge**).

Table 1 : Principal modes of investment and development for conjunctive use of groundwater and surface water resources in the developing world

WATER-SUPPLY DEVELOPMENT		WATER DEMAND CENTRE	
SOURCE	MODE	CROP IRRIGATION	URBAN POPULATION
<i>Surface Water</i>	<i>public</i>	###	###
	<i>public private partnership</i>	#*	##
<i>Groundwater</i>	<i>public – in-situ</i>	##*	###
	<i>public remote wellfield</i>	n/a	#
	<i>private in-situ</i>	###	##***

usual ## *frequent* # *exceptional*

* *sometimes in relation to extension of canal distribution network but not for river diversion*

** *in some cases public or community waterwells constructed for flow-support to irrigation canals*

*** *especially significant where shallow aquifers present to allow low-cost waterwell construction*

CONJUNCTIVE USE FOR URBAN WATER-SUPPLY

Strategies to Improve Water-Service Security

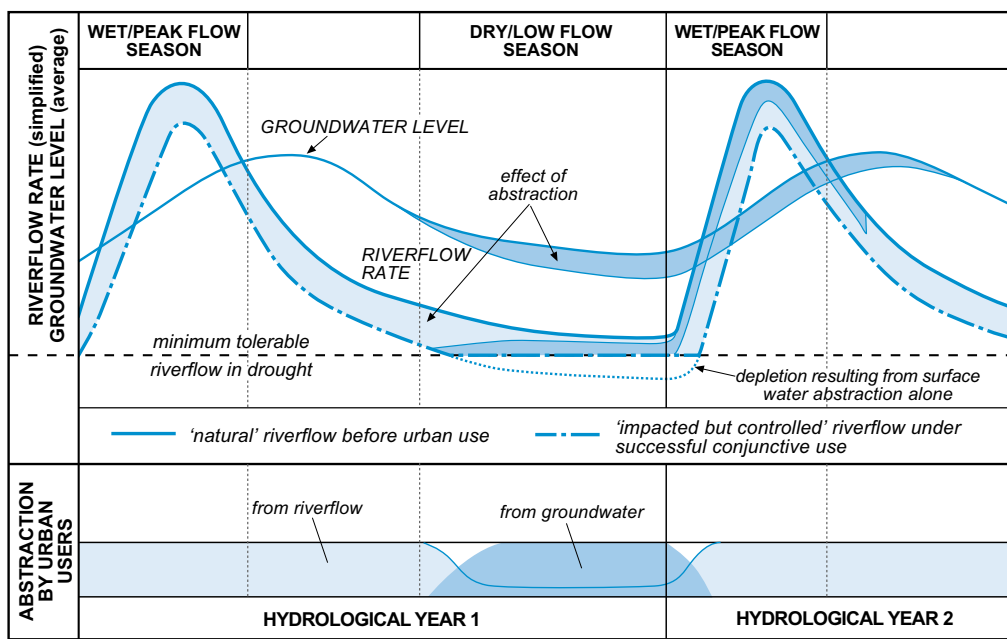
- The form of urban conjunctive use of groundwater and surface water sources most commonly encountered at present in the developing world amounts to a ‘piecemeal engineering coping strategy’ in which :
 - waterwells have been drilled by (or for) the municipal water utility on an ad-hoc basis in newly-constructed suburbs to meet their water demand at lowest possible capital cost, independently of the existing urban water-supply system
 - surface water has been imported from a major new distant source to reduce dependency on waterwells in the older parts of a city because of pollution fears.

Box A features Lucknow-India and clearly represents the short-term benefits of ‘piecemeal conjunctive use’ but the pressing need for a more planned and comprehensive approach.

- Another frequent occurrence (Table 1) is that private domestic and commercial users in urban areas construct waterwells for in-situ self-supply, frequently as a ‘coping strategy’ when confronted with unavailability, poor levels or high prices of utility water-supply. Clearly this is another form of unplanned and sub-optimized conjunctive use in situations where the utility water-supply is drawn primarily from surface water sources.
- However, there are examples of more integrated and optimized schemes (**Box B** on Lima-Peru is a good example), where the key to full development of conjunctive use was not simply related to source development but also to the engineering of a mains-water distribution system that allows the majority of urban users to be supplied from different sources at different times.
- Looked at from a hydrological standpoint, there are two distinct types of urban ‘conjunctive use setting’ which require a somewhat different technical appraisal and operational strategy :
 - utilizing groundwater from an aquifer which is hydraulically-independent of the main river system from which surface water is drawn
 - utilizing groundwater from an aquifer in hydraulic continuity with river (Figure 1a).
 Both require appropriate technical feasibility analysis but the latter setting needs much more careful initial evaluation and refinement (adaptive management) through long-term monitoring and numerical modelling.
- The criteria on which the operational strategy of urban conjunctive use is most normally based (Figure 2) are :
 - abstract preferentially from the river whilst its flow-level is above the minimum required for ‘downstream’ wastewater assimilation and dilution and/or ecological interests (except where river-water is periodically not treatable because of high suspended solids and/or pollution)
 - use waterwells at other times, especially during extended drought when surface-water availability is limited – whenever possible ensuring that the impact of waterwell abstraction is mainly delayed until higher riverflow periods.

One source may, however, not always be capable of completely substituting the other for capacity reasons, and it is the balance between the use of the two sources that is varied. An alternative operational strategy sometimes adopted is to minimise operational costs (pumping of groundwater

Figure 2 : Typical hydrological modifications caused by successful conjunctive use of groundwater and surface-water resources for urban water-supply



versus treatment of surface water) – but this could imply sacrificing other important conjunctive use benefits, such as improved supply security and/or increased supply capacity.

Overcoming the Main Impediments to Planned Conjunctive Use

- The most common impediments to the full development of conjunctive use for urban water-supply in the developing world are :
 - frequent split responsibility for surface water and groundwater management (and also development) between local (provincial or state) government, municipal authorities, and sometimes even involving national government (in some cases under the control of different political parties), resulting in failure to identify and to engineer opportunities for planned conjunctive use
 - lack of sound and intelligible information about conjunctive use opportunities, which can be communicated to politicians and the general public, because of the absence of an ‘Information and Communication Unit’ at the relevant level of local water resource agencies
 - urban water engineers often tend to look only for operationally-simple set-ups, such as a major surface water-source and large treatment works, rather than more secure and robust conjunctive use solutions and do not adequately appreciate the benefits which rational development of groundwater resources offers
 - urban water-service utilities are often politically or institutionally constrained from proposing the development and protection of urban wellfields in favorable areas (where high yields and good quality can be obtained), located outside the city’s municipal limits
 - inadequate understanding of the extent of private in-situ self-supply with groundwater from shallow aquifers, its benefits and its risks.

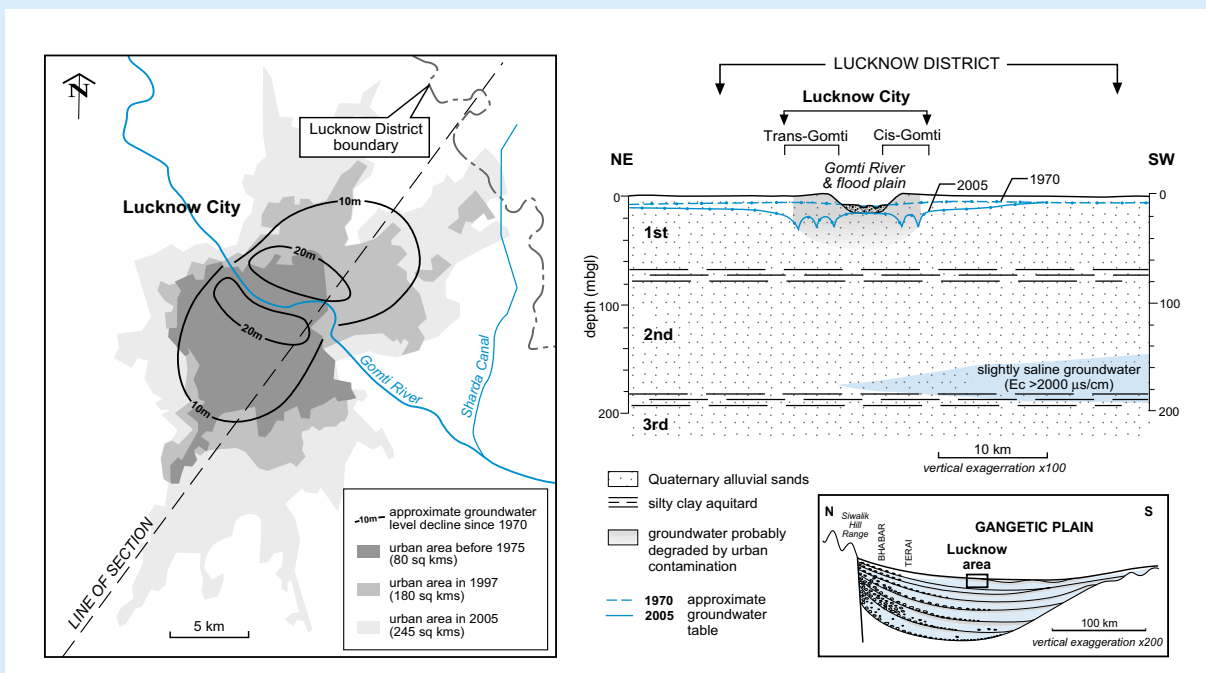
Box A LUCKNOW-INDIA

A HISTORY OF INCIDENTAL CONJUNCTIVE USE FOR URBAN WATER-SUPPLY NEEDING FUTURE EXPANSION AND HARMONISATION

Lucknow City is situated on the banks of the Gomti River in the Central Ganga alluvial plain and underlain by Quaternary alluvial sands and silts, with ‘three more productive groundwater horizons’ in the uppermost 300m separated by interbedded silty-clay aquitards (Figure A1). There are significant but subtle spatial variations in the aquifer – including slightly-saline groundwater over the depth range 140-200 m bgl across the ‘cis-Gomti’ area (Figure A1). The climate is sub-tropical with 1140 mm/a average rainfall, the majority normally falling during the June-September monsoon, but in some years the monsoon rains can be much reduced. Since 1892 Lucknow had a limited public water-supply network (based on a small intake and treatment works on the lowland Gomti River) but the population of Lucknow Metropolitan Area grew very rapidly from the 1950s (0.3-0.4 million) to 2.3 million in 2001, and is projected to reach 4.0 million by 2020.

Conjunctive use commenced ‘incidentally’ from 1973, following construction of the first tubewells for the Lucknow Municipal Water Utility (LJS) – they were of 120 m depth with a static water-level of around 10-12 m bgl and tapped only the ‘second productive level’ by setting intake screens from below 65 m depth (Figure A1). But in an effort to meet rapid urban growth and spiraling water-demand, by 2005 over 300 municipal tubewells had been drilled within the city area (with the more recent 200-350 m deep completed at 200 mm diameter or larger). The gross municipal supply available increased to 490 MI/d, of which around 240 MI/d derives from groundwater and 250 MI/d from surface water (with the River Gomti intake having been replaced by a Sardhar Irrigation Canal offtake, because local groundwater abstraction had greatly reduced baseflow and its quality had deteriorated due to wastewater discharge). In some areas there has also been rapidly increasing private waterwell construction, in essence as a ‘coping strategy’ by those seeking and prepared to pay more for a secure continuous supply.

Figure A1 : Lucknow District – simplified map and sections showing hydrogeological setting, rate of urban growth and water-table decline during 1975-2005



In the 1950s, the pre-monsoon water-table depth appears to have been mainly less than 10 m bgl, but today it has been widely depressed to below 20 m bgl (Figure A1), has passed 30 m bgl in some areas, and continues to decline at rates in excess of 1.0 m/a. In consequence tubewell yields have reduced significantly, although long-term availability of groundwater resources remains good and current problems are more related to localized over-abstraction than to absolute resource shortage. However, all LJS tubewells deliver raw water quality conforming with current Indian drinking water norms, although many private tubewells tapping the 'first productive level' record elevated NO_3 concentrations (over 100 mg/l) and in other cases dissolved Fe and Mn problems are reported – suggesting locally heavy DOC and N load from wastewater infiltration causing reducing conditions initially and at greater depth progressive in-situ oxidation.

Today the LJS operational position can be summarized as follows :

- the growth in urban demand and groundwater level decline has resulted in the need for a 'major public works effort' to construct and commission 40 new tubewells per year and to recondition many others
- substantial physical leakage losses (estimated around 30% overall), especially from older sections of the distribution network, reduce deployable supply to about 345 MI/d
- some source and distribution limitations, such as 6 hours/day service at low pressure is typical, with individual use at about 100 lpc/day (except in a few areas with better service and some outlying colonies dependent on water tankers).

Like most 'alluvial groundwater cities' (metropolitan areas where local groundwater from alluvial deposits provides a substantial proportion of municipal water-supply), there is a smaller differential between the economic cost of municipal supply (running costs of US \$ 0.10/m³ – although current charging results in users only paying US \$ 0.04/m³ average) compared to private tubewell water-supply (capital and running cost of US \$ 0.15-0.30/m³).

Municipal water engineers tend to favour reducing dependence on groundwater (because of its operational complexity) and opting for a major new surface water transfer scheme. There are plans to augment further Sardhar Canal flows from the Upper Ghaghara Basin (150 km or so distant) in an attempt to guarantee the availability of 500 MI/d in all seasons at the city canal offtake – but such a scheme would be highly vulnerable to climate-change impacts (long-term baseflow reductions from the Himalayan mountain chain due to glacier recession) and agricultural sector competition (potential drought conflicts with the farming community across whose land the canal runs). Moreover, the 2025 demand prediction for Lucknow City requires a gross available supply of 810 MI/d (before leakage losses are deducted), which would imply maintaining or even expanding local groundwater production. Thus the more robust way to face the future urban water-supply challenge is to evolve to :

- a more harmonised conjunctive use of groundwater and surface water, including much more rational tubewell site selection (rather than proximity to new demand centres and constrained by municipal political boundaries)
- the development of rural protected wellfields within 30 km of Lucknow City (for example in areas which are experiencing soil waterlogging as a result of high and/or rising water-table where there would be a secondary benefit of improving land drainage and crop productivity)
- improved interconnectivity of the main water-supply network such that a larger proportion of users can be provided from either type of source.

The implementation of such a strategy depends greatly on the UP-State Water Resources Agency (SWaRA), supported by the Central Groundwater Board (CGWB) Regional Office in respect of groundwater resource assessment and numerical modelling, leading a constructive dialogue with the LJS and WSSB (UP- Water-Supply & Sanitation Board) on future water-supply source options.

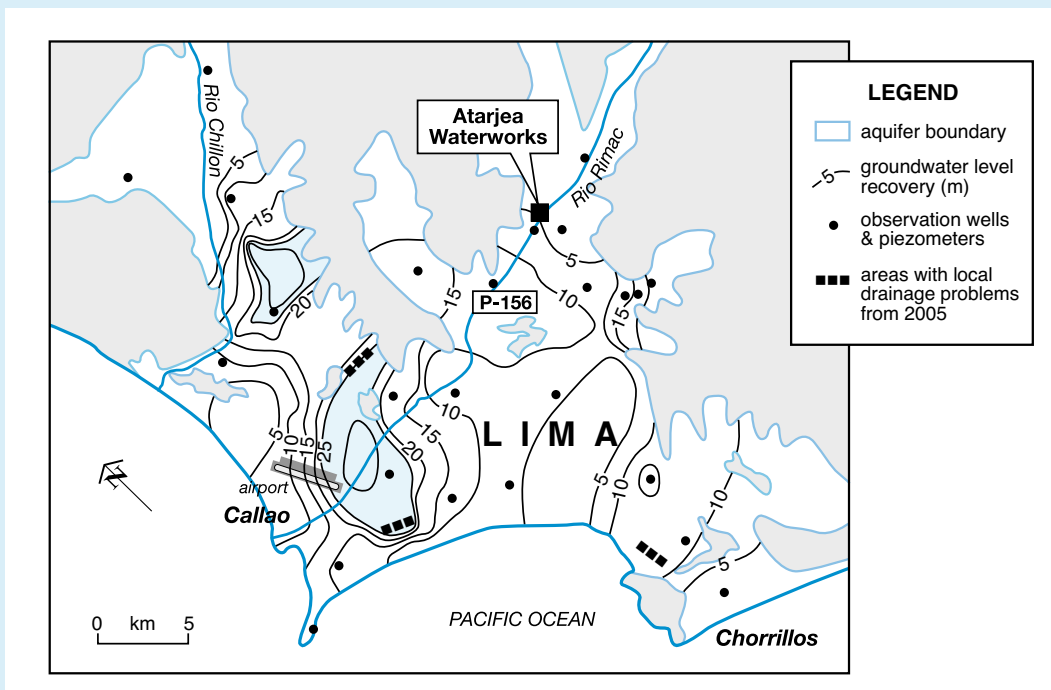
Box B
LIMA - PERU

SUCCESSFUL LONG-TERM ACTION ON CONJUNCTIVE USE AND DEMAND MANAGEMENT TO STABILISE URBAN WATER-SUPPLY AND GROUNDWATER RESERVES

The conurbation of Greater Lima extends across the Quaternary alluvial outwash fans of the Rimac and Chillón rivers, which occupy about 390 km² of the extremely arid coastal plain of Peru (Figure B1). The underlying alluvial aquifer has a saturated thickness of up to 300m, but the upper 100m or so (of sandy gravels) provide the best yields to waterwells. Recharge to the alluvial aquifer system arises from riverbed infiltration (recently enhanced), by seepage from irrigation canals and excess irrigation to agricultural crops, parks and gardens (reducing overall because of urbanization and more controlled irrigation techniques) and by leakage from water-supply mains and wastewater infiltration (which until recently was increasing) – with the current total estimate put at around 190 Mm³/a.

During the 1960s-1980s the city grew very rapidly to a population of over 8.0 million – and its demand for water-supply increased from less than 100 MI/d in 1955 to more than 2000 MI/d in 1997 (of which some 1580 MI/d was provided by SEDAPAL, the municipal water-supply utility). The Atarjea Waterworks on the Rimac river was commissioned in 1956 with a capacity to produce 430 MI/d and this was increased to 860 MI/d in 1969 — although production is not possible at times of maximum riverflow and suspended solids because of treatment problems, and is also less secure in drought, although progressive upstream inter-catchment transfer has increased flow-security to over 90%. Of the total water-supply in 1997, 1050 MI/d was derived from groundwater (380 SEDAPAL and about 800 industrial/commercial waterwells abstracting 720 MI/d and 330 MI/d respectively) with a resultant continuous water-table decline of 1-5 m/a (the water-table reaching over 100m depth in some areas) (Figure B1). This caused waterwell yield reductions, escalating pumping energy costs and groundwater quality decline in some areas due to saline water intrusion. There has always been a element of conjunctive use in the water-supply of the city, but this was constrained because many districts could only be supplied from groundwater.

Figure B1 : Distribution of Rimac-Chillón alluvial outwash fan aquifer system and water-table recovery during Aug 1997 - Dec 2003



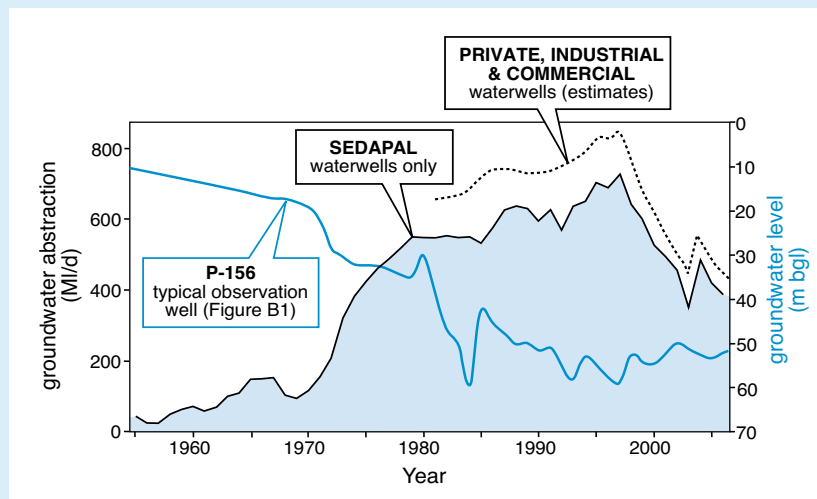
During 1985-95 major studies and investments were made to optimize conjunctive use of surface water and ground-water resources, and to manage the water-demand of the city, and thereby to stabilise this important aquifer and conserve its strategic reserves and to improve urban water-supply availability through:

- a concerted micro-measurement campaign of domestic water use (costing about US\$ 60 million and involving metering of 700,000 users) and industrial groundwater conservation (costing about US\$ 10 million), to reduce demand through wastage reduction
- an additional Andean surface-water transfer up to 260 MI/d to the Rimac River (costing US\$ 63 million), to improve flow-security and which also had benefits in terms of energy generation and increased treatment plant capacity at the Rimac River intake to 1500 MI/d
- improved flexibility of water distribution in the city, to allow a much higher proportion of users to be supplied either from treated riverwater or from groundwater (involving installation of 66.8 km of additional water mains at a total cost of about US\$ 22 million)
- riverbed recharge enhancement measures over 6 km of the Rimac River (costing US\$ 12 million), including 60 transverse riverbed baffles totalling 10,000m length, 30 waterwells of 80-120m depth with a pumping capacity of 140 MI/d and a comprehensive monitoring set-up.

The institutional arrangements for the implementation of the above measures were unconventional. In 1981 a Decreto Supremo charged and empowered SEDAPAL (the municipal water company and major groundwater abstractor) to act on behalf of national and regional government to conserve Lima’s strategic groundwater reserve – following the introduction of abstraction licensing and given their strong ‘on-the-ground operational presence’. SEDAPAL established a special office and team for the purpose, in effect acting as a ‘contractor’ to government for this task, but referred all key policy decisions to IRH and SUNASS (the national water resources institute and water-service regulator respectively). The measures used included a ban on waterwell drilling in some particularly ‘critical areas’.

The success of the conjunctive use and demand management measures is witnessed by the major recuperation of the water-table over wide areas by 5-30 m during 1997-2003 (Figure B1) – following a decline of 10-40 m during the preceding 10 years (Figure B2). Groundwater abstraction by SEDAPAL has reduced from 265 Mm³/a in 1997 to the 2005-09 average of 135 Mm³/a (which represents a decrease from 45% to 21% of the gross public water-supply production), although the capacity to reach much higher rates of production in the short-term still exists. The corresponding figures for industrial/commercial direct use are a decrease from 125 Mm³/a to 75 Mm³/a – bringing the overall proportion of urban water-supply from groundwater to 57% in 1997 reducing to an average of 29% in recent years.

Figure B2 : Historical evolution of SEDAPAL waterwell abstraction and water-table depth in the Rimac-Chillon Aquifer



- All such impediments need to be confronted by state or provincial water resource agencies engaging closely with local municipal authorities and the corresponding water utility, and in some cases even with the national water resource agency. Systematic and realistic studies need to be undertaken of technically sound and administratively reasonable options for fully-integrated conjunctive use of groundwater and surface water that would be in the long-term interest of urban water-supply security. In so doing an important corollary that must be addressed concomitantly is making best use of the growing wastewater resource being generated from urban areas, which should be integrated as part of overall water resource planning for conjunctive use in urban water-supply.

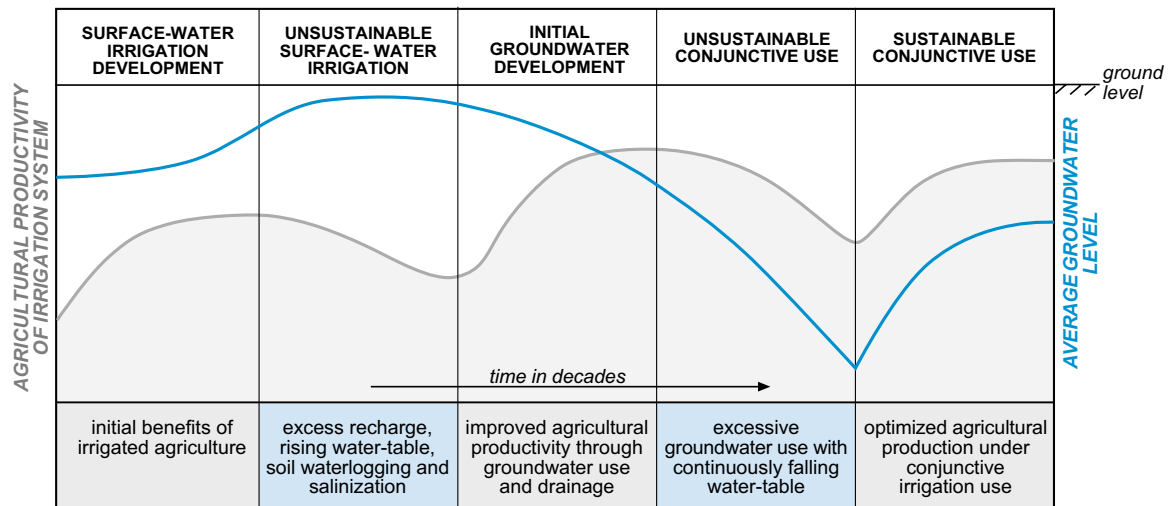
PANORAMA IN MAJOR IRRIGATION CANAL COMMANDS

Spontaneous Sub-Optimal Conjunctive Use by Farmers

- The commonest circumstance in which spontaneous conjunctive use of groundwater and surface water arises 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
 - tied to rigid canal-water delivery schedules and unable to respond to crop needs.
- Any combination of these leads to inadequate irrigation-water service levels throughout much of the canal system and especially towards the tail-end sections. Thus private waterwell drilling usually proliferates, especially around the tail-end sections of the 'irrigation system', and a high dependence on groundwater (often with local excessive exploitation) follows (Figure 3). For instance recent surveys show that :
 - in 14 (out of 23) large-scale irrigation canal commands in the arid terrain of Pakistan less than 50% of the water applied to fields derives from the canal system with most of the rest coming from groundwater and the remainder from rainfall
 - in the Indian States of Punjab and Uttar Pradesh over 70% of the irrigation water-supply is derived from waterwells, albeit that part of the groundwater resource being used originates as irrigation-canal seepage and a minor part from aquifer reserves.

It should also be noted that in a few areas, the order of development of surface water and groundwater resources is different, with canal water introduction through surface water transfer schemes into originally groundwater-only irrigation areas.
- It is noteworthy that private groundwater use is very often characterized by higher water productivity (in terms of kg per ha crop/m³ or US\$ benefit per ha/m³), despite (or perhaps because of) the fact that the unit cost of this water-supply to the user is much higher. But this essentially spontaneous (unplanned, unregulated and unmanaged) groundwater resource use sometimes results in aquifer depletion to water-table levels (Figure 3) that complicate the deployment of low-cost ground-level lift pumps for irrigation and/or that induce saline groundwater encroachment.

Figure 3 : Typical evolution of spontaneous conjunctive use of surface-water and groundwater resources for irrigated agriculture on a major alluvial plain



Groundwater Resource Sustainability Limits

- The potential for (and dynamics of) conjunctive use in agricultural irrigation varies considerably with ‘hydrogeological setting’, including such factors as average rainfall and geomorphological position. Bearing in mind that we are mainly concerned with alluvial plains, some generalizations on water resource availability and constraints for irrigated agriculture can be given – in terms of these different settings (Table 2).

- In some instances spontaneous conjunctive use encounters the problem of increasing groundwater salinity, which if not adequately diagnosed and controlled will result in a serious subsequent decline in agricultural productivity and also become a threat to the security of drinking-water supplies.

Groundwater salinity threats arise by one of a number of completely distinct mechanisms :

- rising water-table due to excessive canal seepage and/or field application in head-water areas leading to soil waterlogging and salinization, or sometimes naturally saline phreatic groundwater becoming mobilized especially in land-surface depressions (Figure 4A)
- leaching of soil salinity to groundwater throughout irrigation areas due to first habilitation of arid soils and/or fractionation of salts during ‘efficient’ irrigation, with subsequent accumulation at the water-table (Figure 4B) and around the tail-end sections of irrigation canal commands if no groundwater discharge/drainage occurs (**Box C** illustrates the experience of partially successful measures to counteract this type of problem from Mendoza-Argentina)
- more classical intrusion and encroachment of saline groundwater due to excessive abstraction of fresh groundwater (Figure 4C), both in arid inland basins and coastal areas
- additionally there are hyper-arid areas in which virtually all groundwater is naturally saline, except where some infiltration occurs from surface watercourses and irrigation canals to form ‘freshwater lenses’ (Figure 4D), requiring very careful management as a reliable source of drinking-water supply and supplementary irrigation to avoid on the one hand saline up-coning and on the other

Table 2 : Variation of the dynamics and constraints of conjunctive use with hydrogeological setting

HYDROGEOLOGICAL TYPOLOGY	EXAMPLE(s)	DYNAMICS OF CONJUNCTIVE USE	CONSTRAINTS ON CONJUNCTIVE USE
Upstream Humid or Arid Outwash Peneplain	Indian Punjab-Indus Peneplain, Upper Oases Mendoza-Argentina, Yaqui Valley, Sonora-Mexico	deep groundwater table with major groundwater recharge from rivers and unlined canals, where riverflow reduces seasonally groundwater use predominates	in more arid areas widespread natural soil salinity which can be mobilised to groundwater during irrigation development and requires careful management
Humid but Drought-Prone Middle Alluvial Plain	Middle Gangetic Plain-India, Middle Chao Phya Basin-Thailand	shallow groundwater table and surface-water and groundwater resources generally freely available	excessive recharge in canal head-water sections can lead to serious soil water-logging/salinity and poor canal-water service levels in tail-end sections causing excessive groundwater pumping
Hyper-Arid Middle Alluvial Plain	Middle Indus Plain-Pakistan, Lower Ica Valley-Peru, Tadla – Morocco, Tihama - Yemen	major rivers and primary irrigation canals generate locally important fresh groundwater recharge/lenses, in some cases further augmented by spate irrigation	conjunctive use of groundwater important to counter rising water-table problems, and concomitantly reach higher cropping intensity, but extreme care needed to avoid saline-water encroachment
Downstream Alluvial Plain or Delta with Confined Groundwater	Ganges Delta-Bangladesh, Lower Oasis Mendoza-Argentina, Nile Delta-Egypt	irrigation predominantly from major rivers and associated canals but, where seasonal riverflow reduction marked, supplementary groundwater irrigation can be important	alluvial aquifers often semi-confined by surficial clayey-silts (also sometimes with saline phreatic groundwater) – thus waterwell use constrained by recharge limitation and sometimes by saline-water mobilisation

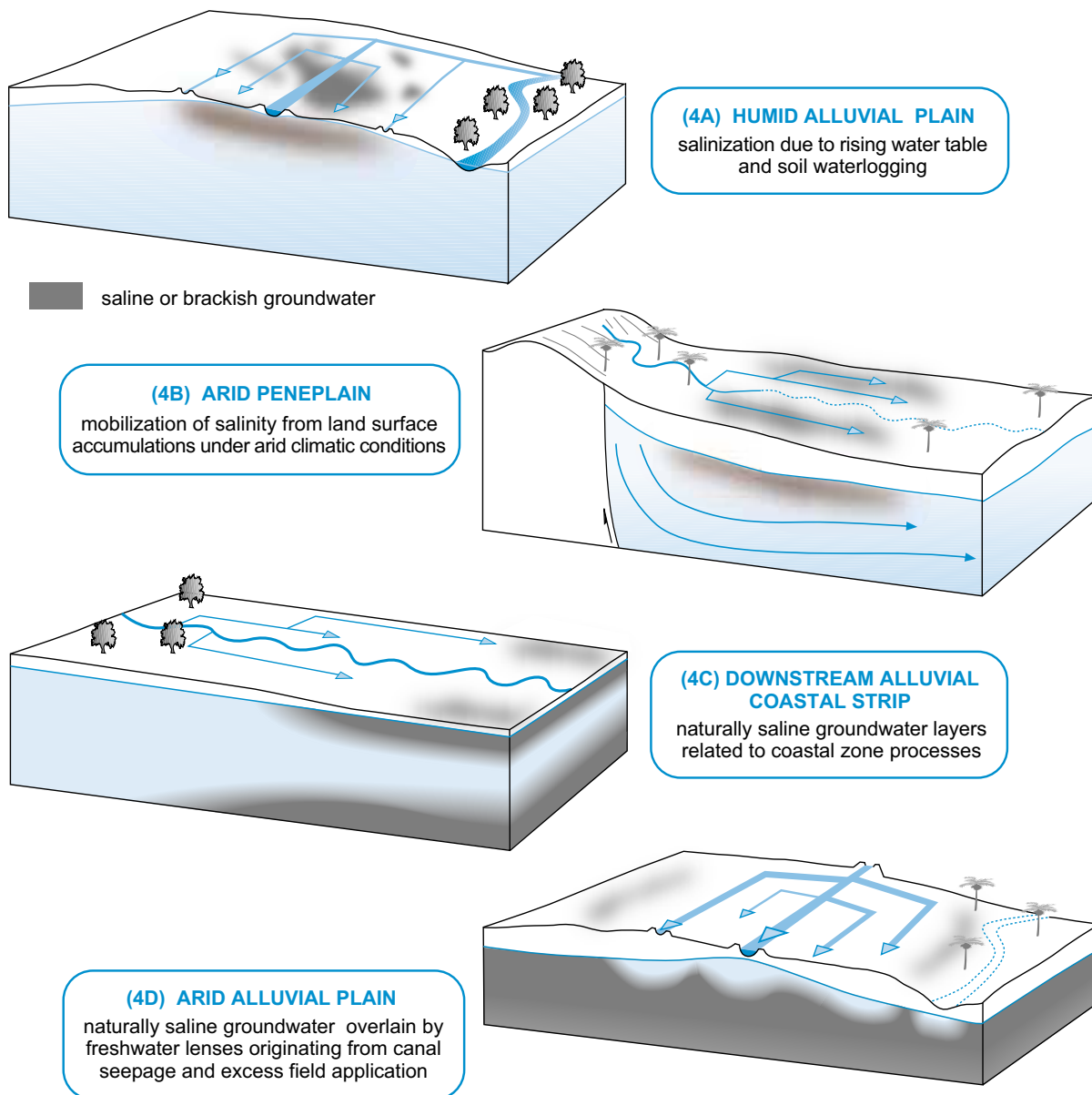
excessive infiltration and water-table rise accompanied by salinization – in the entire Middle & Lower Indus Valley of Pakistan examples of this condition exist, with the extension and thickness of freshwater lenses tending to decrease downstream to a minimum in parts of Sindh Province.

- The lining of primary and secondary irrigation-canals will be a high priority :
 - on arid alluvial plains where the phreatic aquifer is naturally saline (with fresh groundwater confined at greater depth), since canal seepage will often represent a non-recoverable resource loss contributing to rising water-table, soil waterlogging and salinization
 - on humid alluvial plains with rising water-table in a shallow fresh groundwater system, since excessive canal seepage will be contributing to soil waterlogging and associated secondary salinization.

- In sharp contrast, on highly permeable alluvial terraces and peneplains (especially in more arid areas) the secondary and tertiary canal systems are often found to carry water for relatively few

days per annum and the majority of irrigation users depend entirely on waterwells – as in the case in extensive areas of the Indian Punjab. However, this is still regarded as conjunctive use since canal seepage is responsible for the greater part of aquifer recharge. An important corollary is that any attempt to line these canals to ‘save water’ for use in other areas can be very detrimental to existing conjunctive use because canal seepage provides an important component of aquifer recharge – and careful water resource impact assessment is needed to avoid counterproductive ‘double accounting’.

Figure 4 : Groundwater salinisation mechanisms that can threaten sustainability of the conjunctive use of groundwater and surface water



Box C MENDOZA - ARGENTINA

REFINING CONJUNCTIVE USE PRACTICES IN IRRIGATED AGRICULTURE TO CONFRONT PROBLEMS OF INCREASING GROUNDWATER SALINITY

The DGI (Departamento General de Irrigacion) is a modern autonomous provincial-level water resource agency, which takes a proactive approach to water provision, and has been attempting to integrate groundwater more consistently into the provincial hydraulic infrastructure, which has a long history of surface water management for irrigated agriculture. In this hyper-arid province (with less than 200 mm/a rainfall) substantial volumes of groundwater are stored in the Quaternary aquifer system, which is recharged directly from the Mendoza and Tununyan rivers as they emerge from the Andean mountain chain onto very permeable alluvial outwash fans – and thus the initial approach was to :

- encourage irrigation waterwell drilling in areas outside, and on the margins of, existing irrigation-canal commands
- permit waterwell drilling within surface-water irrigation commands if existing canal allocations did not provide a reliable supply at times of low riverflow and/or maximum plant demand.

This strategy has generally been a great success – as witnessed by the fact that agricultural land prices have reached very high levels (US\$ 30,000-50,000/ha for established vineyards with irrigation infrastructure and groundwater use rights compared to US\$ 4,000/ha for neighbouring barren land). But the strategy has run into problems in two areas where the aquifer response was different to that expected – and in particular where increasing groundwater salinity has occurred impacting the productivity, and questioning the sustainability, of high-value vineyards and orchards.

Figure C1 : Hydrogeological section of Carrizal Valley to show groundwater salinity problem

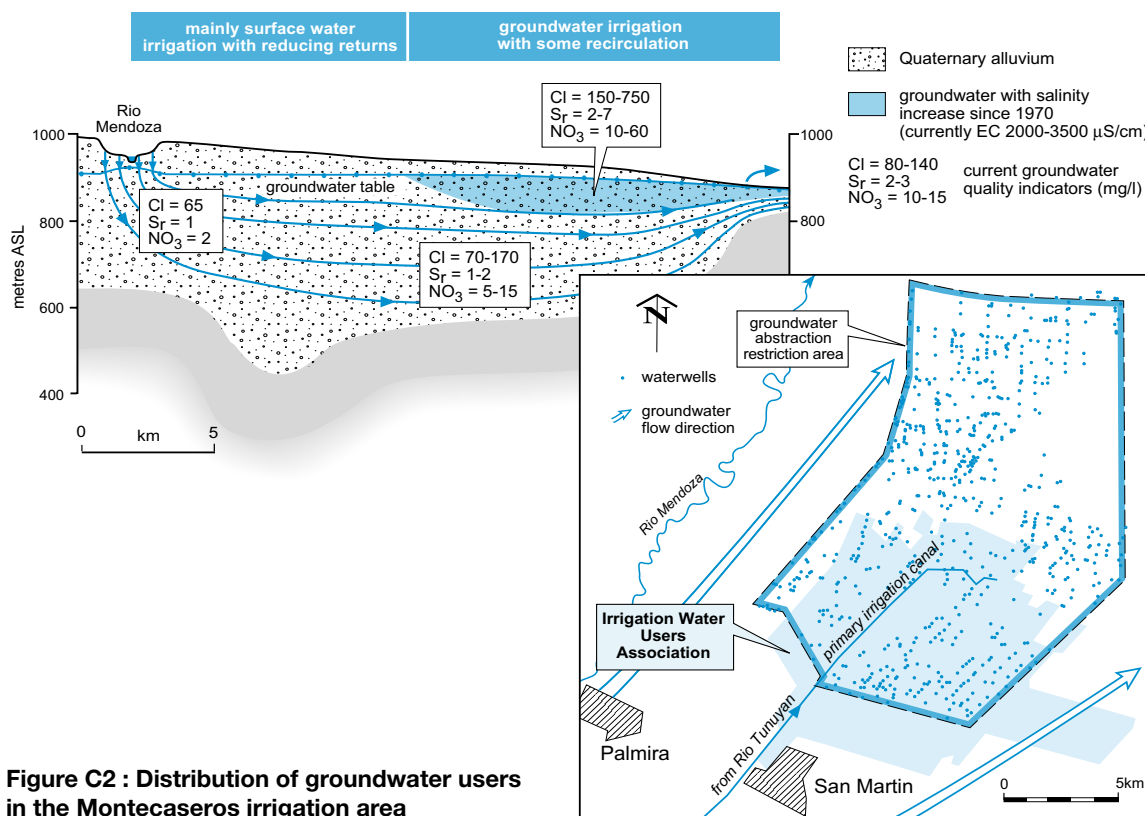


Figure C2 : Distribution of groundwater users in the Montecaseros irrigation area

The first problematic area is the 'upstream' Carrizal Valley (Figure C1), which occupies about 240 km² of Lujan de Cuyo District and whose unconfined aquifer was estimated (pre-2000) to receive an average recharge of 85 Mm³/a from a 10 km stretch of the Mendoza riverbed plus some 40 Mm³/a from surface water irrigation returns. However, subsequent modifications due to riverflow diversion (with 'clear water effects') and increasing drip irrigation (on 14,000 ha of cultivated land) are yet to be fully assessed. The valley's 600-700 waterwells have elevated use factors, and from 1995 an incipient falling water-table (from deep levels of 50m or more) has been recorded. Investigations have revealed a clear stratification of groundwater salinity with troublesome levels for fruit irrigation (EC 2,500-4,000 uS/cm) down to depths of 70 m bgl over a substantial area (Figure C1), and only wells with deep intake screens record an EC less than 2,000 uS/cm – compared to values of 1,800 and 1,000 uS/cm respectively in the late 1960s. The origin of the increasing salinity is the mobilisation of salt accumulated in the vadose zone below natural arid-zone vegetation when the land is brought under irrigation and this is further aggravated by fractionation during groundwater irrigation returns. The key to reversing the groundwater salinity trend is :

- controlling total abstraction such that natural discharge of shallow groundwater continues to occur
- preventing the further spread of irrigated agriculture on saline desert land.

The second problematic area is the 'downstream' Montecaseros zone occupying some 23 km² of San Martin District in the Mendoza 'northern oasis' (Figure C2). This is 30 km distant from the main alluvial-fan recharge area where the aquifer system exhibits marked layering into sub-aquifer units separated by aquitards. Groundwater salinity in the shallowest sub-aquifer (with water-table at 5-15 m depth) increased from 1,000-1,500 uS/cm in the 1970s to 4,500-5,500 uS/cm by 1995 – and the entire groundwater abstraction of 60-85 Mm³/a is now drawn from deeper waterwells screened in deeper sub-aquifers, but the salinity increase has begun to penetrate downward.

The strategy that has been taken on groundwater management and the specific measures adopted include variously :

- more rigorous waterwell drilling controls through declaration of areas of restriction (1997 and 1995 respectively in Carrizal and Montecaseros) to prevent further growth of groundwater abstraction
- severely constraining the spatial transfer of groundwater use rights to avoid further mobilisation of salinity, through a regulation to 'plug a legal loophole' (2008 in Carrizal only)
- intensifying the monitoring of groundwater levels and salinity, coupled with numerical aquifer modelling to provide an improved scientific basis for conjunctive use management
- providing additional surface water-supply by diverting excess riverflows to the areas concerned and improving irrigation canal hydraulic characteristics
- augmenting recharge by works in the Mendoza riverbed (Carrizal) and plugging poorly-constructed and/or highly-corroded waterwells to prevent downward migration of brackish water (Montecaseros).

However, significant legal and social impediments still have to be overcome in the promotion of this strategy :

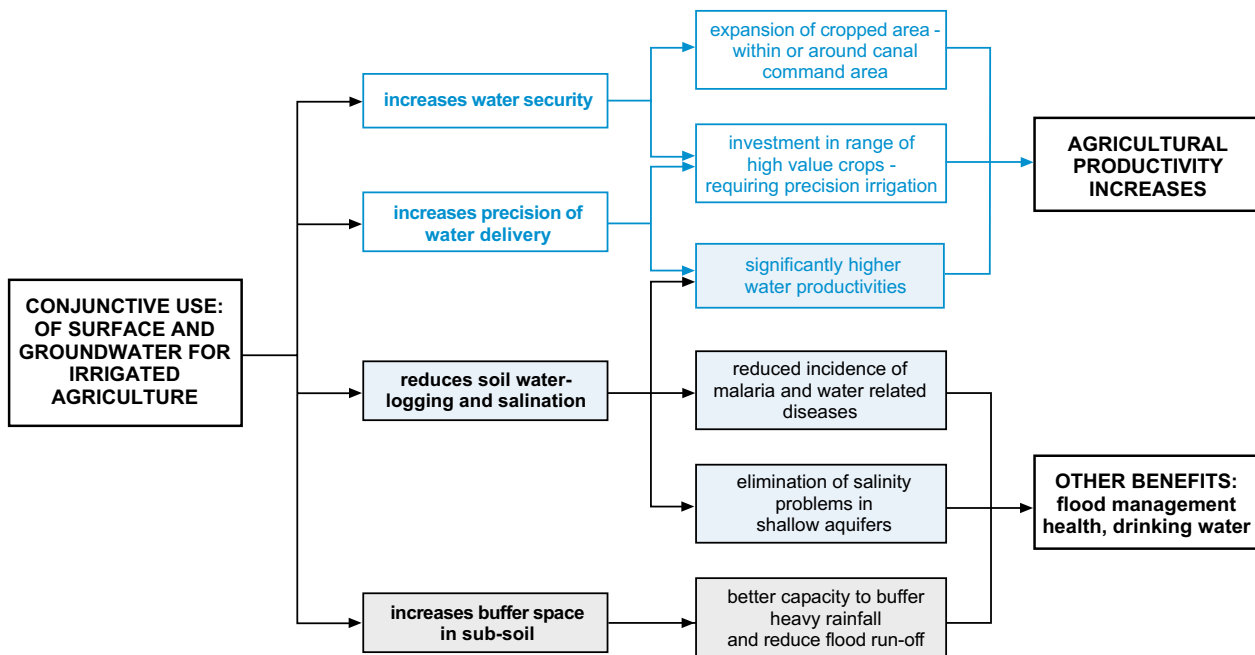
- establishing effective dialogue with groundwater-only users who prefer to remain outside the long-established framework of irrigation canal water-use associations
 - working with groundwater rights in perpetuity by long tradition, despite the changing aquifer dynamics caused by the rapid spread of drip irrigation resulting in much higher consumptive use of groundwater even when licensed abstraction remains constant
 - working with major differentials (up to 500%) in the cost to the irrigation user of groundwater compared to surface-water supply (despite the modest rural electrical subsidy) because provincial government bears a substantial part (40%) of the cost of capital depreciation and periodic rehabilitation of major irrigation canals.
- Nevertheless, the strategy adopted in the Carrizal Valley at least appears to be succeeding, in as much as post-2007 monitoring indicates a partial water-table recovery and decreasing shallow groundwater salinity.

- Clearly there are upper limits on how much groundwater can sustainably be abstracted on a conjunctive basis with a surface water source for consumptive use in agricultural irrigation, for any given hydrogeological setting and surface-water delivery scenario. Where groundwater storage is large (which is normally the case), it will be the ‘long-term recharge rates’ (averages or trends) over the entire area under consideration that will constrain conjunctive use development – and the key issue is to find a balance of groundwater use which avoids long-term water-table decline whilst also countering rising water-table and the menace of land-waterlogging and soil salinization.
- In this context it is **absolutely essential to note that (for all unconfined water-table aquifers), an important component of total groundwater recharge will actually be from ‘irrigation returns’ (irrigation-canal seepage and excess application of surface water at field level)** – and any measures taken to improve ‘irrigation water distribution and application efficiency’ are likely to impact on groundwater resource availability (see **GW•MATE Briefing Note 16 on Groundwater Resource Accounting**). Detailed design consideration will also need to be given to waterwell interference during extended drought, to potential salinity issues (and how many cycles of irrigation reuse are feasible) and to the impact of upstream groundwater use on downstream dry-weather river baseflow. Stemming from this it will be necessary to identify and to avoid the risk of ‘double water resource accounting’ in areas of major conjunctive use of surface water and groundwater.
- The issuing of water rights in conjunctive use areas needs to be performed on a careful and ‘integrated basis’ recognizing that surface water and groundwater are usually hydraulically-linked in alluvial aquifers, and thus :
 - this relation needs to be reflected in the total volume of water use rights granted
 - groundwater development will imply some reduction in surface water availability.
 This is often not straightforward since in some canal commands surface water use entitlements are often ‘area based’ and not ‘volume controlled’, and traditionally take no account of access to groundwater.

Advantages of Better Planned Conjunctive Use

- The benefits that can accrue from improving the planning and management of conjunctive use, both for existing and new agricultural irrigation areas, are summarized in Figure 5 from which it will be evident that these benefits also vary with ‘hydrogeological setting’ and some will be specific only to certain settings.
- Integrated numerical modelling of irrigation canal flows, groundwater use and aquifer response, soil-water status and crop water-use (Figure 6) are a great aid to evaluating the potential benefits of varying the spatial and temporal use of groundwater and distribution of surface water, and thus of improving conjunctive use efficiency and sustainability.
- **The most important advantage, however, is that agricultural production can usually be increased considerably (through improvements in overall cropping intensity and irrigation water productivity) without compromising groundwater use sustainability** – and Box D provides a classic example of this situation from the Gangetic Plain of Uttar Pradesh-India.

Figure 5 : Range of potential benefits of conjunctive use of groundwater and surface water resources



- Fully planned and managed conjunctive use offers the possibility of being able to ‘control water-table depth’ and seasonal variation of the shallow alluvial aquifer, and the pros and cons of different ‘engineered groundwater table depths’ in the command area of conjunctive use irrigation schemes are :
 - < 0.06 m : only beneficial for some specialised crops – with major soil waterlogging and soil salinization hazard, important non-beneficial evaporation losses, increased health hazard from malaria and liver-fluke, and sanitation difficulties
 - 0.06 – 1.60 m : optimum for a wide range of crops – but if significant ‘micro-relief’ may still be above problems related to waterlogging occurring in land depressions
 - > 1.60 m : also suitable for most crops, except high water-using species – but risk of drought stress and groundwater pumping costs progressively increase.
- In the most ambitious of planned conjunctive use schemes for agricultural irrigation, abstraction from the respective source can be optimized, not only with respect to surface water resource availability and distribution but also with respect to reducing evaporative losses in surface water storage reservoirs and minimizing the actual energy costs of irrigation (in terms of kWhr/ha).
- On alluvial plains downstream of major urban areas, large quantities of only partially-treated wastewater are often available (most notably in the dry season) for agricultural irrigation. This requires careful spatial planning and operational control to maximise the groundwater resource benefits whilst minimizing the groundwater pollution risks – but this topic is considered outside the scope of the current review.

Box D

UTTAR PRADESH - INDIA

THE POTENTIAL FOR IRRIGATED AGRICULTURE IN MOVING FROM SPONTANEOUS COPING STRATEGY TO PLANNED CONJUNCTIVE USE

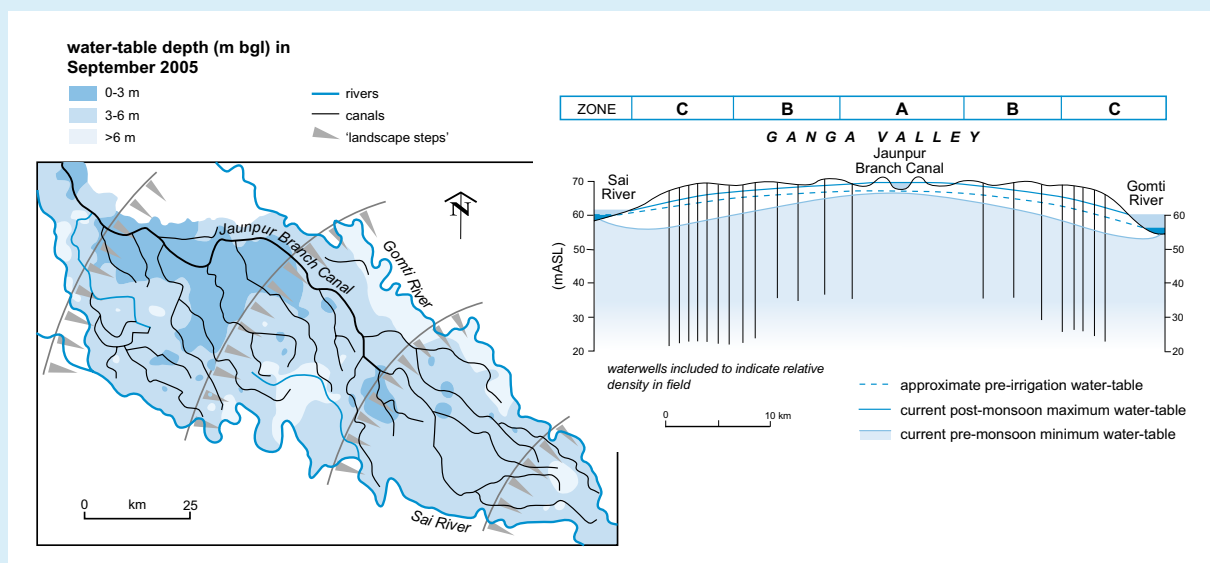
The vast alluvial tracts of the Ganges Valley are underlain by an extensive aquifer system of layered sand-silt deposits (up to 600 m thick), which represents one of the largest groundwater storage reserves in the world. These alluvial aquifers exhibit generally good waterwell yield potential (even to tubewells of only moderate depth), and are recharged directly from infiltrating monsoon rainfall (local annual average rainfall generally above 1,600 mm/a) and indirectly from surface-water via irrigation canal leakage and excess field application. Large-scale groundwater use for agricultural irrigation has developed spontaneously as a coping strategy by farmers experiencing inadequate or unreliable service from canal irrigation systems – and shows potential as an adaptation strategy for climate change scenarios predicting progressive reduction of Himalayan glaciers and of associated baseflows in the main Ganges tributaries.

The main kharif (hot wet season) and rabi (cool dry season) crops are rice and wheat respectively, accounting for almost 70% of all crops grown, although sugar-cane can locally reach 40% of the total in irrigation canal head-water zones. Groundwater use has widely increased to represent as much as 70% of overall irrigation water-supply, despite very limited coverage of rural electrification and dependence on diesel-engine pumps. With recent increases of hydrocarbon fuel prices, groundwater users have been paying US\$ 100-150/ha for pumping groundwater as compared to US\$ 5/ha for canal water-use.

As a result of intensive groundwater use for irrigation over 50% of the Uttar Pradesh land area now has a falling water-table, whose impacts are increasingly evident in terms of irrigation tubewell dewatering, yield reduction and pump failure, together with hand-pump failure in rural water-supply wells. Concomitantly, and sometimes in relatively close proximity (10-20 km distant) to the ‘groundwater overexploitation zones’, canal leakage and flood irrigation in the ‘head-water zones’ is resulting in around 20% of the land area being threatened by rising and shallow water-table, with soil water-logging and salinisation leading to crop losses and even land abandonment.

This situation has been evaluated in considerable hydrogeologic, agronomic and socioeconomic detail in the Jaunpur Branch canal-command area (Figure D1), between the Ghagara and Gomti Rivers in central Uttar Pradesh. Integrated numerical modelling (of crops, soil, canal and aquifer) based on excellent field data here clearly shows that more

Figure D1 : Post-monsoon depth to water-table and hydrogeological cross-section for the alluvial aquifer of the Jaunpur Branch - Uttar Pradesh



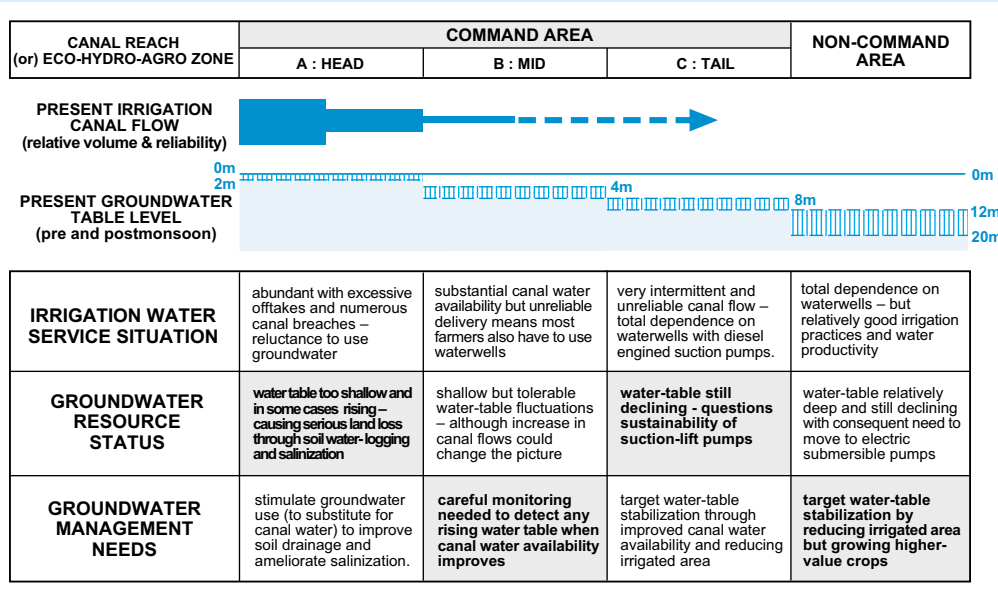
‘optimised conjunctive use’ (with improved surface water distribution and use, complemented by more rational groundwater use) could increase the cropping intensity from the current average level of about 140% to around 220%, by reducing the growing sodic land problem and without compromising groundwater resource sustainability.

An attempt is being made to implement a ‘more planned conjunctive-use approach’ through :

- completing and maintaining bank sealing and de-sedimentation of major irrigation canals
- enforcing existing ‘operational codes’ for the distribution of canal water
- promoting the construction and use of tubewells (if necessary through subsidy and eventually through rural electrification) not only in non-command areas but also in high water-table areas
- financial investment and specialist extension in soil salinity mitigation and sodic land reclamation.

And most importantly, pursuing an appropriate management action plan, for which purpose the land surface has been sub-divided on the basis of hydrogeologic and agroeconomic criteria into a number of small ‘micro-planning and -management zones’, with specification of the required management measures to move to more efficient and sustainable conjunctive use (Figure D2). In this context it is noteworthy that the highest current cropping intensities are in those parts of the irrigation canal head-water zones which are irrigated only by tubewells (where all illegal canal breaches and off-takes have been sealed) and the most productive water-use in those tail-end zones largely or entirely dependent on groundwater where crop diversification has been introduced. Another measure that could be considered would be to pursue water-saving for the rice crop by delaying paddy transplanting for a few weeks from May (when gross evaporation rates exceed 10 mm/d) to June, which through state government ordinance in the Punjab in 2008 proved capable of significantly reducing consumptive water demand without compromising rice yields, with enforcement achieved under penal legislation by widely publicising any violations.

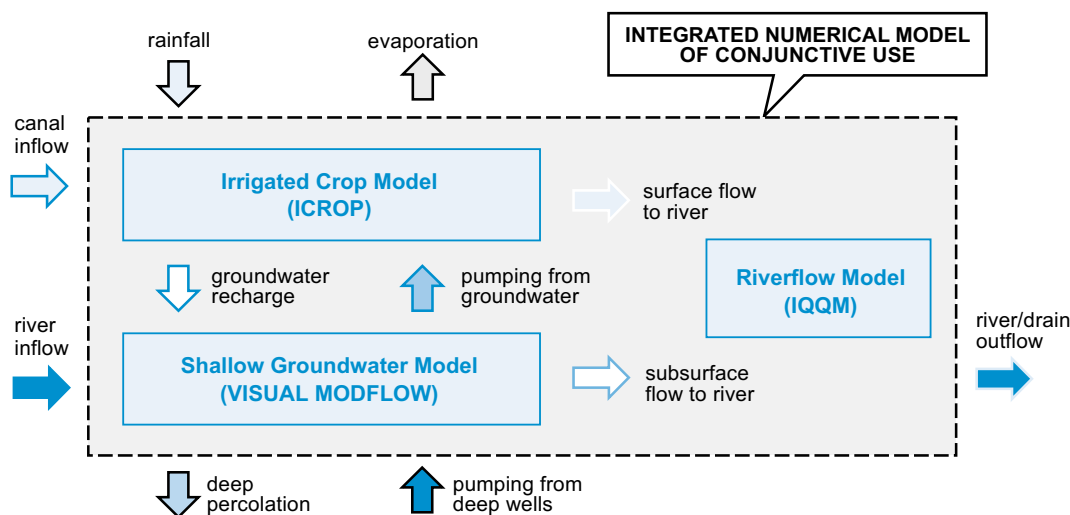
Figure D2 : Micro-land zoning for successful management of groundwater and irrigation in Uttar Pradesh



The promotion of more planned and integrated conjunctive use is having to overcome significant socioeconomic impediments through institutional reforms, public investments and practical measures including :

- the introduction of a new over-arching state government apex agency for water resources (SWaRA), because existing agencies tended to ‘mirror’ historical sector water-supply fragmentation and irrigation canal development, and were thus tending to perpetuate (rather than reform) the ‘status quo’ on water-supply distribution and utilisation
- 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.

Figure 6: Scheme of integrated numerical modelling to evaluate conjunctive use options for improving the efficiency and sustainability of irrigated agriculture



Overcoming the Main Impediments to Planned Conjunctive Use

- All too often there is split responsibility for surface water and groundwater development and/or surface water and groundwater management, and this commonly results in a failure to identify and to engineer opportunities for planned conjunctive use. There is often considerable rigidity, and resistance to change, in the distribution of surface-water supply, whose rationalization is a necessary pre-condition and important instrument for promoting more efficient conjunctive use. This rigidity and resistance often relates to a narrow focus on surface-water delivery and canal-water rostering – with social groups holding tightly onto long-standing entitlements, rather than to absolute water-resource scarcity.
- The impediments to promoting more rational and better planned conjunctive use in established irrigation-canal command areas can thus be significant – and usually fall into the categories of :
 - socio-political sensitivity and unwillingness of farmers in areas that are relatively well-endowed with surface water to reduce surface intakes and rights, and allow a greater proportion of available canal water to reach less endowed areas
 - inadequate understanding of conjunctive use and the potential role of groundwater by water resource and irrigation engineers, since it is poorly taught in academic engineering centres
 - the fact that water organizations and agencies often tend to ‘mirror’ historical irrigation water-supply development realities and as such tend to perpetuate the social status quo and do not grasp conjunctive use opportunities
 - in some cases lack of rural electrification and reliable electricity supplies for groundwater pumping in major irrigation-canal command areas
 - inadequate water resource and supply charging systems with large cost differential (as felt by users) between groundwater and surface water for irrigation – because of traditional politic of providing canal water at very low-cost (often not even collecting the cost of operation and maintenance let alone capital cost recovery) – factors of x 10 to x 20 are commonplace, but vary according to

whether diesel-engined pumps or subsidized rural electricity grid available, and on the depth to water-table, well yield potential, etc.

- These impediments have to be overcome by :
 - a long-term campaign of education (about the risks of waterlogging and salinization and collateral benefits of groundwater pumping)
 - design criteria (Table 3) and incentives for balanced groundwater use (since it is unlikely to be politically feasible to increase significantly the cost to users of canal-water supplies)
 - delegation, within a sustainable and transparent framework, of the issuing of groundwater and surface-water use rights on an integrated basis to appropriate irrigation water-user associations (IWUAs).

Intriguingly, the deterioration of surface-water delivery in canal commands during prolonged drought often results in a rise (rather than a decline) in agricultural productivity since it triggers more groundwater development and conjunctive use.

Table 3 : Planning Conjunctive Use of Groundwater for Irrigated Agriculture - Management Measures & Instruments

GROUNDWATER PARAMETER	RELATED CONSIDERATIONS	MANAGEMENT MEASURES & INSTRUMENTS
Aquifer Characteristics	storage capacity of shallow and intermediate depth aquifers critical	preferable for surface-water irrigation systems to avoid areas underlain by low permeability strata, which are likely to result in soil waterlogging and salinisation unless elaborate and costly drainage provided
Recharge Excess in Local Groundwater Balance (rising groundwater table and soil waterlogging)	balance needs to be struck between groundwater recharge and discharge by all mechanisms operative – and any ‘excess recharge’ used productively	surface-water diversion can be curtailed so to reduce excess recharge to groundwater
		private waterwell development may be stimulated through a range of incentives
		land reclamation and drainage measures may be required to kick-start intensive cultivation in a given area
Recharge Deficit in Local Groundwater Balance (falling groundwater table and saline encroachment)	balance needs to be restored between groundwater recharge and discharge through waterwell use	surface-water resources may be diverted and reallocated with corresponding reduction in direct groundwater use
		recharge enhancement measures could be introduced utilising excess surface water flows through irrigation canals
		promote less water-consuming crops on same irrigated area to reduce consumptive water-use
Groundwater Quality	careful diagnosis of any incipient groundwater salinity problems in and around area of irrigation development essential	selective irrigation-canal lining in areas with saline groundwater to prevent further recharge and mobilisation
		supplementary surface water may be supplied in the case of coastal areas experiencing excessive groundwater abstraction and saline intrusion
		in some instances saline groundwater may be put to special use (eg. fish-farming ponds) as part of an overall plan for sustainable groundwater management

- There will also need to be much more committed and enforced administration of available surface-water resources (through the IWUAs), with attempts to incorporate/federate groundwater-only users (those who have as yet no access to surface water) into existing IWUAs – such that groundwater use policy and special administration requirements can become embedded there and represented in higher-level water resource stakeholder committees.

CONCLUDING REMARKS

Technical Foundation

- The evolution to more planned conjunctive use and management of groundwater and surface water resources offers great potential for increasing water-supply security and efficiency for both irrigated agriculture and urban water-supply in the developing world. It will be especially important for climate change adaptation on large alluvial plains, which are often major centres of population and economic development.
- To achieve this end greater emphasis will need to be put on characterizing the behavior of underlying aquifers including :
 - its relation to the dynamics of the associated surface-water regime, both in its natural state and as modified by human activity
 - the occurrence and mechanism of any groundwater salinization, since this represents a major threat to the sustainability of groundwater use and has to be proactively managed.

Institutional Requirements

- The promotion of improved conjunctive use and management of groundwater and surface water resources will also 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 as such 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.
- In many ‘alluvial regions’ the authority and capacity for water resource management are mainly concentrated in a surface-water oriented agency, because of the relationship with the historical development of surface-water management measures (such as impounding reservoirs and major irrigation canals). This has led to little emphasis on complementary and conjunctive groundwater management, with responsibility for this resource in a minor department or completely separate minor agency. Some significant reform of this situation will be essential, with strengthening of the groundwater resource management function and/or creation of an overarching and authoritative

‘apex agency’ for improved, conjunctive and cross-sector, water resources policy and planning. Such agencies will need, in turn, to promote changes in the participation of water users in water resource use and management to better respond to conjunctive use opportunities.

- The four specific cases discussed in detail clearly show that the institutional dimension of conjunctive use management is significantly more complex than where groundwater is the predominant water resource. This is mainly because of divergent interests amongst some users, split government responsibilities and frequent lack of well-trained personnel. Moreover, the institutional requirements to implement management measures call for approaches that tend to be locality specific.
- However a common need is for better information and communication on conjunctive use potential amongst all private and public stakeholders. An Information & Communication effort from the appropriate water resource agency would facilitate the social learning and institutional development process and lead to the promotion of attitude changes and the acceptance of implementable regulations.

Acknowledgements

- The authors wish to express special thanks to Catherine Tovey, the World Bank GW•MATE Manager, for her personal encouragement and systematic review of this paper, and to acknowledge the valuable support of the World Bank-Water Anchor, under the leadership of Julia Bucknall. The initial draft was also improved by the constructive review of Claudia Sadoff, and helpful comments from other participants of a related session at the World Bank Sustainable Development Forum of January 2010. There is also full recognition of the very important contribution of various counterpart organisations in the countries mentioned in the text – especially DGI-Mendoza of Argentina, SWaRA-Uttar Pradesh and LSJ-Lucknow of India, and ANA and SEDAPAL-Lima of Peru. It should also be registered that the views expressed are those of the authors, and not necessarily those of the World Bank.

Further Reading

- Bredehoeft J D & Young R A 1983 *Conjunctive use of surface water and groundwater for irrigated agriculture – risk aversion*. Water Resources Research 19 : 1111-1121.
- Briscoe J 2007 *Pakistan's Water Economy*. Annex 12. (Gohar S & Steenbergen F van/Steenbergen F van & Tuinhof A). Oxford University Press.
- Foster S, Perry C, Hirata R & Garduño H 2009 *Groundwater Resource Accounting – critical for effective management in a 'changing world'*. GW•MATE Briefing Note Series No. 16, World Bank. www.worldbank.org/gwmate
- Foster S, Garduño H, Tuinhof A & Kemper K 2002-2006 *Urban Wastewater as Groundwater Recharge — evaluating and managing the risks and benefits*. GW•MATE Briefing Note Series No. 12, World Bank. www.worldbank.org/gwmate
- Foster S & Choudhary N K 2009 *Lucknow City – India: Groundwater Resource Use & Strategic Planning Needs*. GW•MATE Case Profile Collection No. 23, World Bank. www.worldbank.org/gwmate
- Foster S & Garduño H 2006 *Integrated Approaches to Groundwater Resource Conservation in the Mendoza Aquifers of Argentina*. GW•MATE Case Profile Collection No. 6*, World Bank. www.worldbank.org/gwmate
- Sahuquillo A 2002 *Conjunctive Use of Surface Water and Groundwater*. (in) UNESCO Encyclopedia of Life-Support Systems, ed. Silveira L, Chapter 2.9. EOLSS Publishers.
- Shah T 2009 *Taming the anarchy – groundwater governance in South Asia*. Resources for the Future Press.
- World Bank 2010 *Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India*. World Bank.

Publication Arrangements

The GW•MATE Strategic Overview Series is published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwp.org).

The findings, interpretations, and conclusions expressed in this document are entirely those of the authors and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors, or the countries they represent.

Funding Support



GW•MATE (Groundwater Management Advisory Team) is financed by the World Bank's Water Partnership Program (WPP) multi-donor trust fund provided by the British, Danish & Dutch governments and by supplementary support from the UK Department for International Development (DfID).

