GW•MATE

THE WORLD BANK

Global Water Partnership

WATER PARTNERSHIP PROGRAM

Sustainable Groundwater Management
Contributions to Policy Promotion

Strategic Overview Series Number 4

Sustainable Groundwater Irrigation
approaches to reconciling demand with resources

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The aim of this paper is to provide a strategic overview of a decade of experience in supporting various 'public administrations' around the world in their efforts to manage intensive (and in many cases excessive) groundwater resource exploitation for agricultural irrigation. Special emphasis is put on a number of aquifers, mainly in South & East Asia and Latin America, where GW•MATE has either been involved with the implementation of comprehensive 'pilot' projects over 3-5 years (in Argentina, Brazil, China and Morocco) or been invited to evaluate, advise and guide on-going initiatives (in India, Mexico and Peru). These experiences are profiled through a series of boxes introduced in the overview – each exhibiting a varying degree of success but all providing hope and orientation for the future in this important aspect of water resource management. GW•MATE recommends use of a 'pragmatic framework' to identify of a balanced package of technical, economic, institutional and social measures appropriate to the hydrogeological setting and socioeconomic situation of the aquifer system (or groundwater body) under consideration, that can be introduced with the agreement of stakeholders to promote more sustainable groundwater use in agriculture.

CONTENTS

CONTEXT FOR RESOURCE MANAGEMENT ACTION

The 'Global Boom' in Groundwater Irrigation

- The last 20-40 years have witnessed massive increases in the use of groundwater for irrigation in the more arid regions and in areas that have extended dry seasons and/or regular droughts (except for those in Sub-Saharan Africa). In India, for example, the area irrigated with groundwater has increased 500% since 1960. In developing and transforming nations this 'global boom' has occurred at various economic levels – subsistence farming, staple-crop production and commercial cash-crop cultivation. It has brought major socioeconomic benefits to many rural communities in Asia, Middle East & North Africa and Latin America – with numerous countries establishing large groundwater-dependent economies.

- Groundwater is a 'very popular commodity' with most farmers since :
  - access and use is under their direct control for responding to crop needs as they arise (given availability of a reliable source of energy for pumping)
  - it is usually found close to point-of-use (often only a well's depth away)
  - it is naturally well-suited to pressurised irrigation systems and so-called precision agriculture, which offers greater rewards and security to farmers.

- A large proportion of investment in the construction and equipping of irrigation waterwells has been on a private basis by individual farmers, albeit that this has widely been facilitated and stimulated by government through grants and low-cost loan finance, together with the provision of highly subsidized rural electrical energy for pumping. Having said this it is necessary to point-out that groundwater for irrigation still usually results many times more expensive to users than canal water, because of the widespread lack of capital cost recovery (and also often less than full charging of maintenance costs) for the surface-water irrigation infrastructure.

- Satisfactory statistics on the use of groundwater for agricultural irrigation have only recently become available (**Table 1**) as a result of an UN-FAO initiative. Globally the cultivated area under irrigation is estimated to be about 301 M ha of which 38% is equipped for groundwater irrigation and the

Table 1 : Global survey of land area equipped for and using groundwater irrigation

REGION	GROUNDWATER IRRIGATION AREA		GROUNDWATER VOLUME USED	
	M ha	*propn total*	*km³/a*	*propn total*
GLOBAL	**112.9**	**38%**	**545**	**43%**
South Asia	48.3	57%	262	57%
East Asia	19.3	29%	57	34%
South East Asia	1.0	5%	3	6%
Middle-East & North Africa	12.9	43%	87	44%
Latin America	2.5	18%	8	19%
Sub-Saharan Africa	0.4	6%	2	7%

(data derived from Siebert et al 2010)

associated consumptive irrigation use is put at 545 km^3/a (43% of total irrigation use) – the nations with the largest groundwater equipped areas are India (39 M ha) and China (19 M ha).

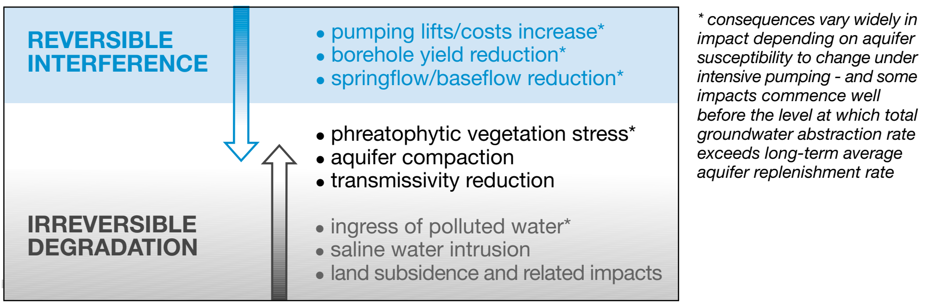
Concern About Resource Depletion and Sustainability

- In most regions with an extended dry season, consumptive water use by agriculture (if unconstrained) usually generates a demand for crop irrigation in excess of the availability of renewable groundwater resources (given that extensive areas of cultivatable land usually occur above aquifers). In some cases inappropriate irrigated agriculture has become established (without planning) through exploitation of non-renewable groundwater resources or very weakly recharged aquifer systems.

- This situation has led to extensive depletion of groundwater resources with a number of collateral effects (**Figure 1**) which vary considerably in occurrence and intensity with hydrogeological setting :
  - counterproductive competition between irrigation users
  - conflicts with rural (and sometimes urban) drinking-water provision from groundwater, both in a quantity and quality sense
  - incipient and progressive aquifer salinization with serious long-term implications for agricultural productivity – which can occur through a range of essentially different mechanisms (**Figure 2**)
  - degradation of important groundwater-dependent aquatic ecosystems.

  A more balanced approach to rationalizing groundwater use in irrigated agriculture is urgently required which recognizes its key role in rural livelihoods but also values its other roles more realistically.

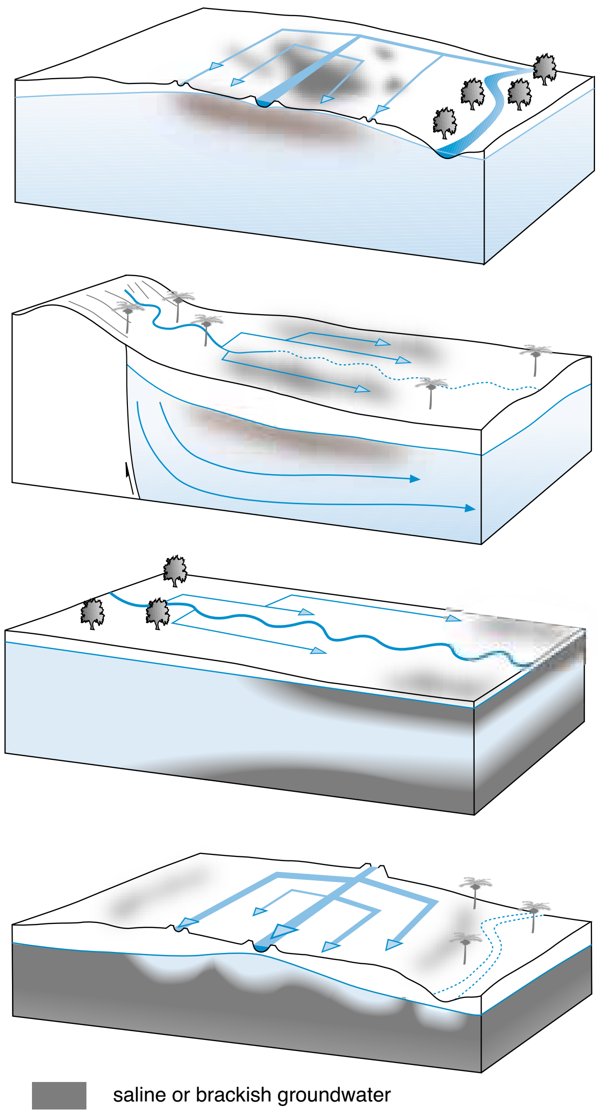
Figure 1: Consequences of excessive groundwater abstraction



- Further philosophical discussion of the interrelated concepts of groundwater resource 'sustainability' and 'overexploitation' is appropriate here, although it is not the intention to get hung-up over semantics. Clearly almost all groundwater abstraction has an 'impact' – in the sense that it diverts groundwater flow from elsewhere in the aquifer system and reduces its natural discharge. The real question is when do such impacts become cumulatively significant ?

- While It may appear appealing to apply economic criteria to the definition of 'groundwater resource overexploitation' (ie: the sum of the costs of third-party effects, longer-term environmental impacts and lost future resource opportunity, clearly exceeding the short-term use benefits), in practice it is often difficult to assess all the costs associated with the former. Moreover, such an approach does not address the 'efficiency versus equity issue', given that less-depleted groundwater systems favor more equitable access for poorer members of society and often also better protect ecological interests.

Figure 2 : Common occurrences of groundwater salinisation and their groundwater management requirements for irrigation use



(A) HUMID FLOOD PLAIN
shallow groundwater salinization caused by rising water-table, soil waterlogging and phreatic evaporation - drainage required to avoid problem and can be achieved by increasing local groundwater use but also equally necessary to reduce irrigation-canal seepage losses

(B) ARID PENEPLAIN TERRACE
mobilization of natural subsoil salinity under native vegetation when land brought into irrigated cultivation - control requires restricting scale of this process and conserving natural aquifer discharge by not overpumping

(C) COASTAL ALLUVIAL BELT
classical saline water up-coning and/or induced downward seepage when vertical hydraulic gradients perturbed by intensive groundwater pumping - careful abstraction control and aquifer monitoring essential

(D) ARID FLOOD PLAIN
freshwater lenses created by riverbed and irrigation-canal seepage forming valuable freah groundwater lenses - requires careful use, management and monitoring to avoid either falling water-table with saline up-coning or rising water-table with soil waterlogging and salinization

- Other related hydrogeological realities also have to be carefully considered :
  - the onset of undesirable side-effects from resource exploitation sometimes occurs before groundwater abstraction exceeds average medium-term replenishment, but the extent to which this occurs varies considerably with local hydrogeological setting and some aquifer systems are much more susceptible to irreversible degradation than others
  - the criteria of maintaining groundwater stocks against all depletion is rarely appropriate, especially in arid regions where, given the long periodicity of major recharge episodes/events, groundwater storage is very important for mitigating the impacts of surface-water drought and for providing time to allow transition to lower water-use economies to evolve.

- In areas where current average annual rainfall is less than 400 mm/a or so, the related rate of diffuse groundwater recharge can fall-off markedly to very low levels, depending on the soil and vegetation cover. Furthermore, 'non-renewable' groundwater resources occur quite widely in the most arid regions and in some deep aquifers elsewhere, due to physical isolation from the land surface. In all such areas the development of groundwater-irrigated agriculture will have occurred under conditions of very limited or negligible contemporary aquifer recharge, and there is need for the public administration and private groundwater users to come to terms with this reality and to plan and manage accordingly through recognizing the dependence upon non-remewable resources whilst:
  - making every effort to ensure high efficiency and productivity of resource use
  - undertaking detailed metering of groundwater abstraction and use, and monitoring and periodic evaluation of aquifer response
  - considering the issue of intergenerational equity by investing in implementable (and periodically refined) 'exit-solutions' either through enabling and nurturing less water-consuming economy and/ or transferring water from external sources.

- Clearly, however, any overview of groundwater use in irrigated agriculture also has to challenge the wisdom of some long-standing agricultural practices and to question the soundness of some new policies including :
  - irrigation of animal feed (typically alfalfa and/or maize) in arid regions using scarce (and in some cases questionably renewable) groundwater
  - continuous (as opposed to occasional supplementary) irrigation of high water-consumption low-value crops (like sugar-cane and paddy rice)
  - use of scarce groundwater resources for the irrigated production of biofuel crops (like maize, soya-bean and sugar-cane).

- It is also necessary to consider the global tendency for reduction in traditional 'spate irrigation' practices (in which agricultural land is deliberately flooded with surface run-off during the wet season to encourage infiltration, groundwater recharge and increased storage availability in the dry season), which although not compatible with investment in modern pressurised irrigation systems is sound practice in terms of water resources conservation in mountainous arid regions.

- It is also extremely important to stress the potential for more planned conjunctive use of groundwater with surface-water resources on major alluvial plains, something which is completely spontaneous and sub-optimized at present, but can increase land and water productivity by simultaneously improving drainage and reducing soil water-logging/ salinization in canal headwater areas and relieving excessive local groundwater exploitation at the tail-ends of irrigation canal systems.

Scope of GW•MATE Experience and Current Overview

- The current overview is based on GW•MATE experience with implementation of comprehensive medium-term pilot projects (**Boxes A-D**) and invited independent assessments of on-going initiatives (**Boxes E-J**), where different measures for groundwater resource management have been introduced in areas of irrigated agriculture (**Figure 3A**) – as part of a broader effort to support public administrations in moving from 'groundwater supply development to 'sustainable resource management'. The GW•MATE experience covers a considerable range of hydrogeological settings, agricultural situations and institutional arrangements, which have been qualitatively assessed to enable rapid comparison (**Figure 3B**)

- In relation to these pilot experiences it should be noted that :
  - the majority refer to settings where groundwater is the only source of irrigation water-supply, although some deal with conjunctive groundwater use (and as indicated above this is considered a very important topic on major alluvial plains – see **GW•MATE Strategic Overview Series 2**
  - most relate to groundwater systems in which environmental discharge and ecosystem dependence is not a primary concern, or where these functions of groundwater have long been lost through an extended history of excessive exploitation, and their recuperation is currently well beyond the targets of national/local authorities involved
  - coincidentally, most have also not focused on rural-urban interactions, although the importance of groundwater management at this critical interface is fully recognized.

In addition, it should be noted that diffuse pollution of groundwater from agricultural land-use practices (through nutrient and pesticide leaching, and increasing salinity of irrigation water returns) is outside the scope of this paper – although the authors' wish to highlight the increasing importance of this subject in the developing world given attempts to increase crop productivity and the potential conflict with conserving drinking water-supply quality.

GENERAL APPROACH TO MANAGEMENT INTERVENTIONS

Assessing the Need for Action by Public Administrations

- Where groundwater exploitation is currently unsustainable it is appropriate to ask the question "it is necessary for the public administration to intervene" – or to allow 'nature to take its course' through steadily rising groundwater production costs (associated with falling water-table and also increasing salinity in some cases), which will eventually act as a disincentive for continued abstraction.

- However, this approach will usually be viewed unacceptable where :
  - the aquifer system concerned is susceptible to irreversible degradation from the intrusion or invasion of saline water or other effects
  - the groundwater user community is highly heterogeneous and continuous water-table decline will essentially eliminate access to drinking and/or livelihood water-supply for the poorer members of the rural community and aggravate social inequality
  - there are no implementable 'exit solutions' to a less water-consuming economy and/or no technically-sound, economically-feasible, socially-acceptable and ecologically-friendly options for alternative water-supply.

- The approach may also have numerous other disadvantages such as :
  - increasing, and in some cases escalating, electrical-energy pumping costs – especially where energy use is 'buffered' by subsidies or flat-rate tariffs for users
  - drawdown interference and sustainability problems for village and small-town groundwater sources, making it more difficult to achieve MDGs

Figure 3A : Location of GW•MATE 'pilot experiences' in World Bank projects for the management of groundwater irrigation

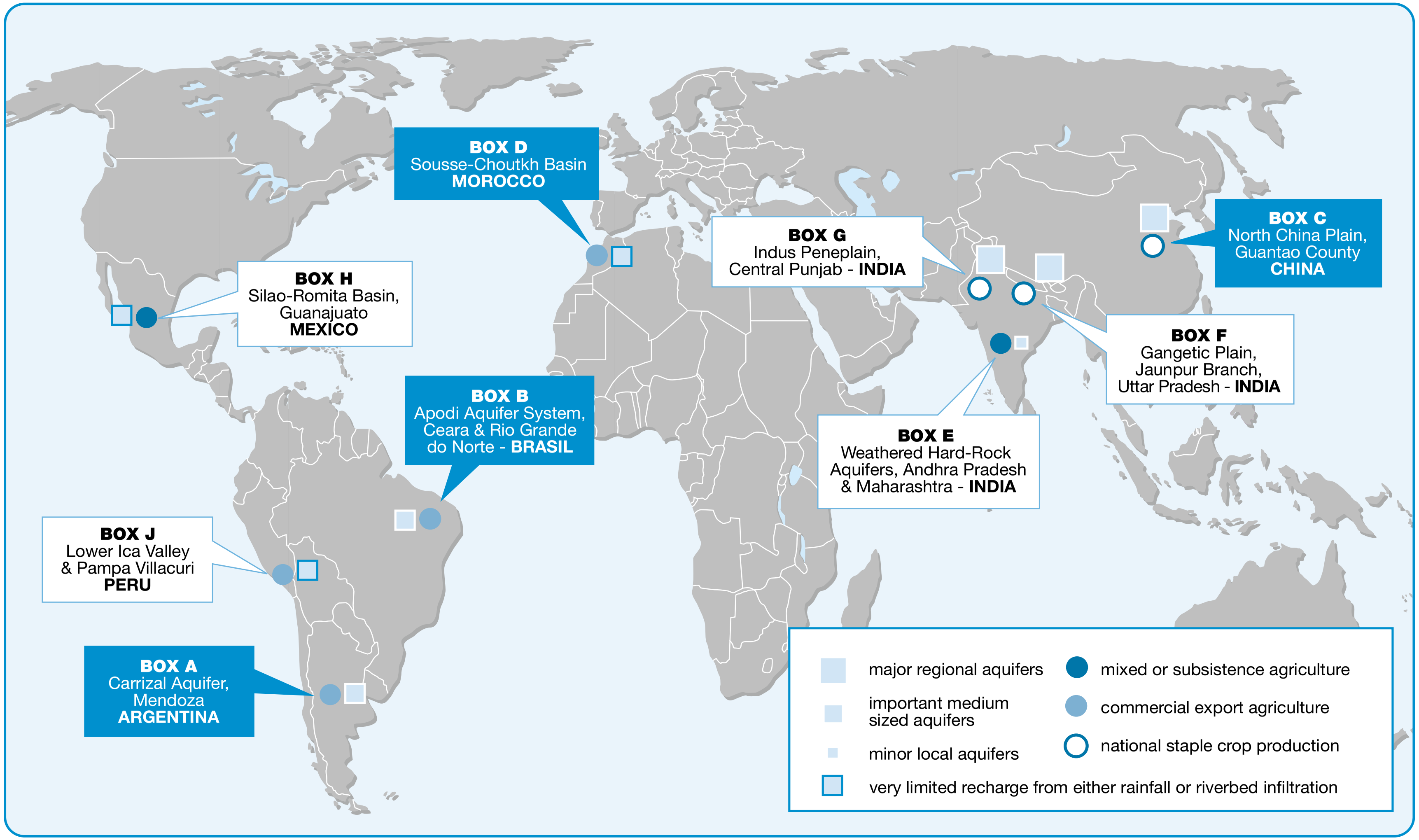


Figure 3B : Classification of GW•MATE 'pilot experiences' in World Bank projects for the management of groundwater irrigation

CHARACTERISTIC	end member	relative position in range														end member
HYDROGEOLOGICAL SETTING OF GROUNDWATER BODY																
Groundwater Diffuse Recharge	weak	PV	MZ	SB	SR	GU			AA	PJ		AP		UP		strong
Groundwater Body Storage	very small	AP		AA		PV	SR	SB	MZ			GU		PJ	UP	very large
Risk of Irreversible Degradation	elevated		GU	PV	MZ	UP	SR	SB	PJ			AA	AP			negligible
Surface Water Connectivity	minimal/slow	PV	AA	AP	SB	SR		GU				PJ	MZ	UP		direct/rapid
DYNAMICS OF GROUNDWATER USE IN AGRICULTURE																
No. & Size of Groundwater Users	modest/major			PV	MZ	AA		SB	SR		GU		UP	PJ	AP	large/minor
Profitability of Agricultural Irrigation	subsistence			AP	SR	UP	GU	PJ				SB	PV	AA	MZ	commercial/export
Irrigation Water Requirement	supplementary					UP	AA	AP	SR	GU	SB	MZ	PJ		PV	continuous
Level of Irrigation Technology	gravity/flood			AP	UP	PJ	SR			SB		GU	AA	MZ	PV	pressurized/drip
INSTITUTIONAL STATUS FOR GROUNDWATER MANAGEMENT																
Political Will	dormant					SR	UP	MZ	GU	AP	SB	PV	AA	PJ		strong
Institutional Capacity	weak		UP	PJ		AP		GU	SB	PV		AA	SR	MZ		strong
Scale of Experience	village	AP		GU	PV	SR	SB	MZ	UP		AA				PJ	major aquifer/basin
User/Stakeholder Organisation	non-existent		UP		PJ	SB		PV		AA	GU	MZ		AP	SR	mature

MZ	**A**: Carrizal Aquifer of Mendoza, Argentina	SB	**D**: Sousse-Choutkh Basin of Agadir, Morocco	PJ	**G**: Indus Peneplain Aquifer of Punjab, India
AA	**B**: Apodi Aquifer System of Ceara and Rio Grande do Norte, Brasil	AP	**E**: Weathered Hard-Rock Aquifer of Andhra Pradesh, India*	SR	**H**: Silao-Romita Basin Aquifer of Guanajuato, Mexico
GU	**C**: North China Plain Aquifer of Guantao County	UP	**F**: Gangetic Alluvial Aquifer of Uttar Pradesh, India	PV	**J**: Pampa Villacuri Aquifer of Ica, Peru*

* *In these instances only one of the two cases described in the corresponding box is profiled in this figure (and the profile of the other case from the same geographic area is significantly different).*

- impacts on natural aquifer discharge (springflow, riverbed flows), which cumulatively impact 'downstream' availability of water resources to an unacceptable degree
- undesirable (and costly) impacts on groundwater-dependent aquatic and/or terrestrial ecosystems.

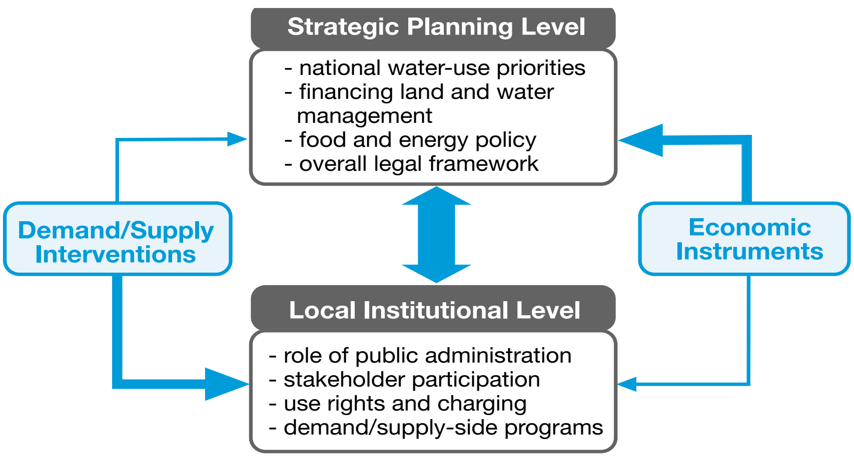
● Thus it is important for public administrations to :
- carefully evaluate the potential cost of 'non-intervention' and its consequences in terms of both environmental irreversibility and socioeconomic impact, and share information on these harsh realities in a frank and transparent fashion with groundwater users, politicians and society at large
- enable and nurture stakeholder participation in order to achieve 'bottom-up' compliance and support, and even community action on groundwater resource management
- critically assess the practicability of either implementing 'command-and-control type measures' (such as waterwell drilling bans, capping borehole yields, partial borehole backfilling, electrical energy rationing, etc), which can be very effective for groundwater resource management but vulnerable to corruption, or adopting a 'more conventional' use regulation approach, which can be problematic in situations with large numbers of individually small users and limited institutional capacity and/or budgets.

Pragmatic Framework for Shaping an Appropriate Action Plan

● GW•MATE experience strongly demonstrates that the hydrogeologic and socioeconomic setting of individual aquifers supporting groundwater-irrigated agricultural development usually both :
- define the groundwater management problem itself, and,
- constrain the most likely management solution and way forward on groundwater use control.

Thus a 'one-size-fits-all' approach to groundwater resource management is simply inadequate. It is necessary to tailor the suite of management instruments and measures deployed in implementation plans to local hydrogeologic and socioeconomic settings, and to strive for harmony between 'bottom-up' measures and 'top-down' incentives (**Figure 4**). At the same time, where groundwater management is concerned, 'perfection is the enemy of good' – and thus an adaptive approach is

Figure 4: Harmonizing 'bottom-up' and 'top-down' measures for groundwater resources management

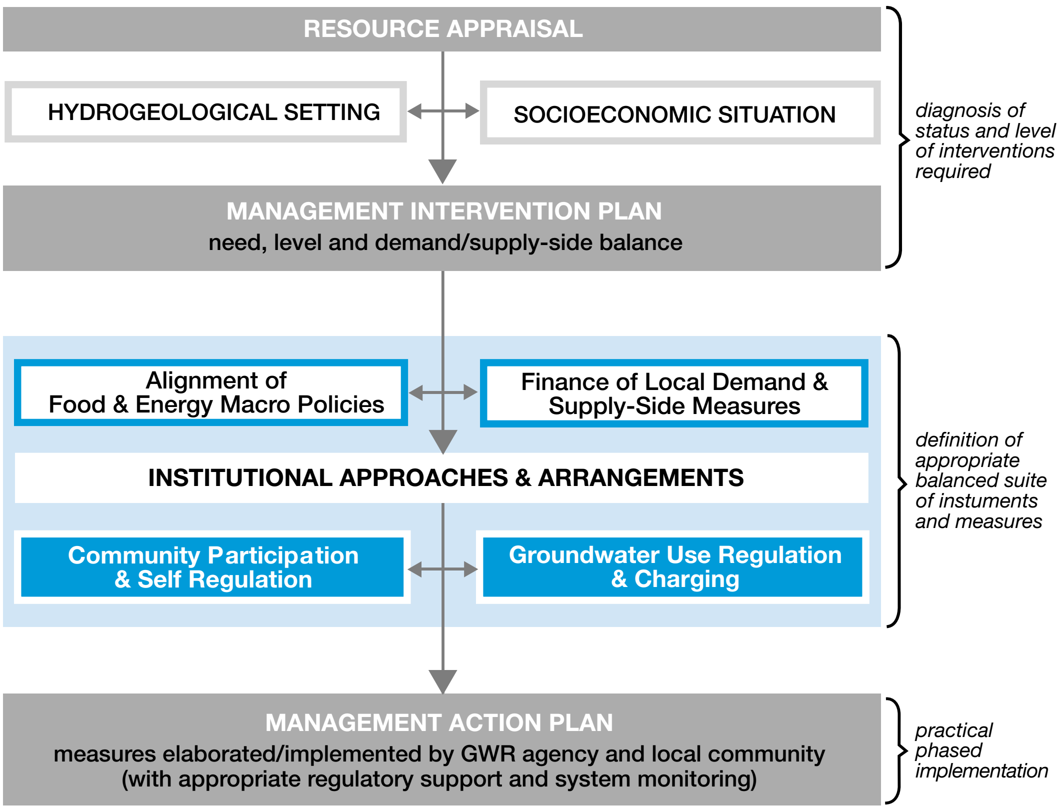


advocated, with periodic review of strategy being guided by progressive improvement in scientific understanding achieved through continuous monitoring and modelling of aquifer system behavior.

- GW•MATE has thus evolved a 'pragmatic framework' (**Figure 5**) to guide a balanced approach towards the elaboration of groundwater resource management strategy between :
  - groundwater resource administration, through use regulation and where appropriate charging
  - community awareness raising, participation and self-regulation
  - financing and promoting demand and supply-side interventions, as technically appropriate and economically-viable (including irrigation technology improvements, water harvesting and recharge enhancement, banning certain crops or crop-cultivation practices, etc)
  - constraining groundwater demand through macro-policy interventions on agricultural crop guarantee pricing, rural electrical energy subsidies, etc.

- In implementing a balanced groundwater resource management policy it will also be necessary to define management targets in terms of future desirable or acceptable groundwater resource status. In terms of establishing stakeholder consensus this can be difficult, since in some cases it has to include realistic resource substitution possibilities and to consider the time available for transition to a less water-dependent economy.

Figure 5 : The GW•MATE pragmatic framework for defining a rational approach to groundwater resource management in excessively-exploited aquifers



Box A (2008)

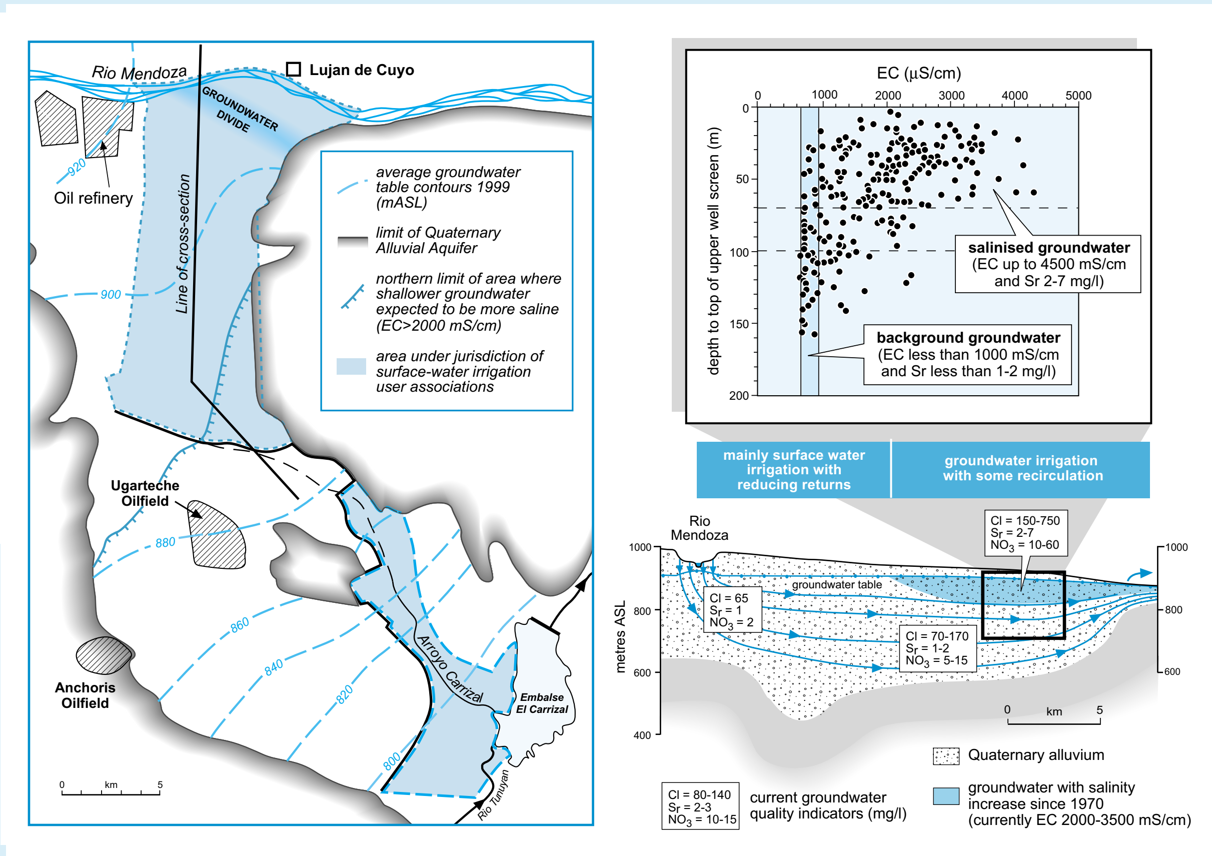
CONFRONTING INCREASING GROUNDWATER SALINITY FOR VITICULTURE UNDER CHANGING CONDITIONS IN THE CARRIZAL AQUIFER OF MENDOZA, ARGENTINA

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 with a long history of surface water management for irrigated agriculture. In this hyperarid area (of around 150 mm/a rainfall) substantial volumes of groundwater are stored in a Quaternary aquifer system recharged directly from the Mendoza and Tununyan rivers as they emerge from the Andean mountains onto very permeable alluvial outwash fans. Thus the initial approach was to :

- encourage irrigation waterwell drilling 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 – witnessed by the fact that land prices have reached very high levels (US$ 30,000-50,000/ha for vineyards with irrigation infrastructure and groundwater use rights compared to US$ 4,000/ha for neighboring barren land). But the strategy has run into problems where increasing groundwater salinity has occurred threatening the productivity, and questioning the sustainability, of high-value vineyards and orchards.

The Carrizal Valley occupies about 240 km^2 of Lujan de Cuyo District and its unconfined aquifer was estimated (pre-2000) to receive an average recharge of 85 Mm^3/a from a 10 km stretch of the Mendoza riverbed plus some 40 Mm^3/a from surface water irrigation returns in a limited area within irrigation-canal command. However, the recharge regime has been substantially modified by :



- upstream river impoundment and partial flow diversion, compensated to some degree by 'clear water' seepage
- a major increase of pressurized drip-irrigation (on more than 14,000 ha of cultivated land).

It will take time and more detailed monitoring to appraise their composite effect.

The valley's 600-700 waterwells have elevated use factors, and since 1995 an incipient falling water-table has been recorded (from already deep levels of 50-100m or more). Recent investigations have also revealed a clear stratification of groundwater salinity with troublesome levels for fruit irrigation (EC 2,500-4,000 µS/cm) down to depths of 70 m bgl over a substantial area, and only wells with deep intake screens recording an EC less than 2,000 µS/cm – this compared to values of 1,800 and 1,000 µS/cm respectively in the late 1960s. The origin of the increasing salinity is the mobilization of salt accumulated in the vadose zone below natural arid-zone vegetation when the land is brought into irrigated cultivation, and this is further aggravated by fractionation during 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 to saline desert land.

The strategy taken on groundwater management and the specific measures adopted include:

- more rigorous waterwell drilling controls – through declaration of areas of restriction in 1997 to prevent further growth of groundwater abstraction
- severely constraining the spatial transfer of groundwater use rights in 2008 to avoid further mobilization of salinity – through a regulation to 'plug a legal loophole'
- intensifying the monitoring of groundwater levels and salinity, coupled with numerical aquifer modelling to provide an improved scientific basis for conjunctive use management
- providing excess riverflows to the area and augmenting recharge by works in the Mendoza riverbed.

However, significant impediments still have to be overcome in promoting this strategy in the long-term :

- establishing effective dialogue with groundwater-only users who prefer to remain outside the long-established framework of irrigation canal water-use associations
- promoting a robust transparent partnership between the public administration and existing irrigators to act in a precautionary way to secure long-term sustainability of groundwater quality and to resist the temptation of shorter-term gains from excessive and imprudent expansion of groundwater use
- working with groundwater rights in perpetuity by long tradition, despite the changing aquifer dynamics caused by the rapid spread of drip irrigation which results in much higher consumptive use even when licensed abstraction remains constant
- accepting a major differential (more than 500 %) in the cost to the irrigation user of groundwater compared to surface-water supply (despite a modest rural electrical energy 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 appears to be having positive results, in as much as post-2007 monitoring indicates a partial water-table recovery and somewhat decreasing shallow groundwater salinity -- trends that need to be confirmed and sustained. A further groundwater management issue that had to be confronted was hydrocarbon pollution (some present together with a major legacy) at the Lujan de Cuyo Oil Refinery & Petrochemical Complex at the northern ('upstream') end of the aquifer system. A public-private partnership was facilitated by GW•MATE in 2002 (between the DGI (public administration) and the REPSOL/YPF oil company) to address these problems in a rational way and to date has raised an investment totaling US$18 million for investigation and remediation of the problems at the large industrial site.

Box B (2009)
CONTROLLING GROUNDWATER USE FOR TROPICAL FRUIT PRODUCTION IN THE TRANS-STATE APODI AQUIFER SYSTEM OF NORTHEAST BRASIL

Since the mid-1990s the groundwater resources of the Chapada do Apodi, which are shared between Ceara and Rio Grande do Norte States, have been subject to rapid development for irrigation of highly-profitable export-quality tropical fruit production (melon, water-melon, pineapple, mango, papaya, guava). The associated capital investment for groundwater irrigation of more than US$ 75 million over a total area of about 8,000 ha has given a major economic boost to this drought-prone area (average rainfall 700-800 mm/a), which since the 1960s had depended upon rain-fed and pest-blighted cotton production, and prior to that limited cattle ranching and forestry.

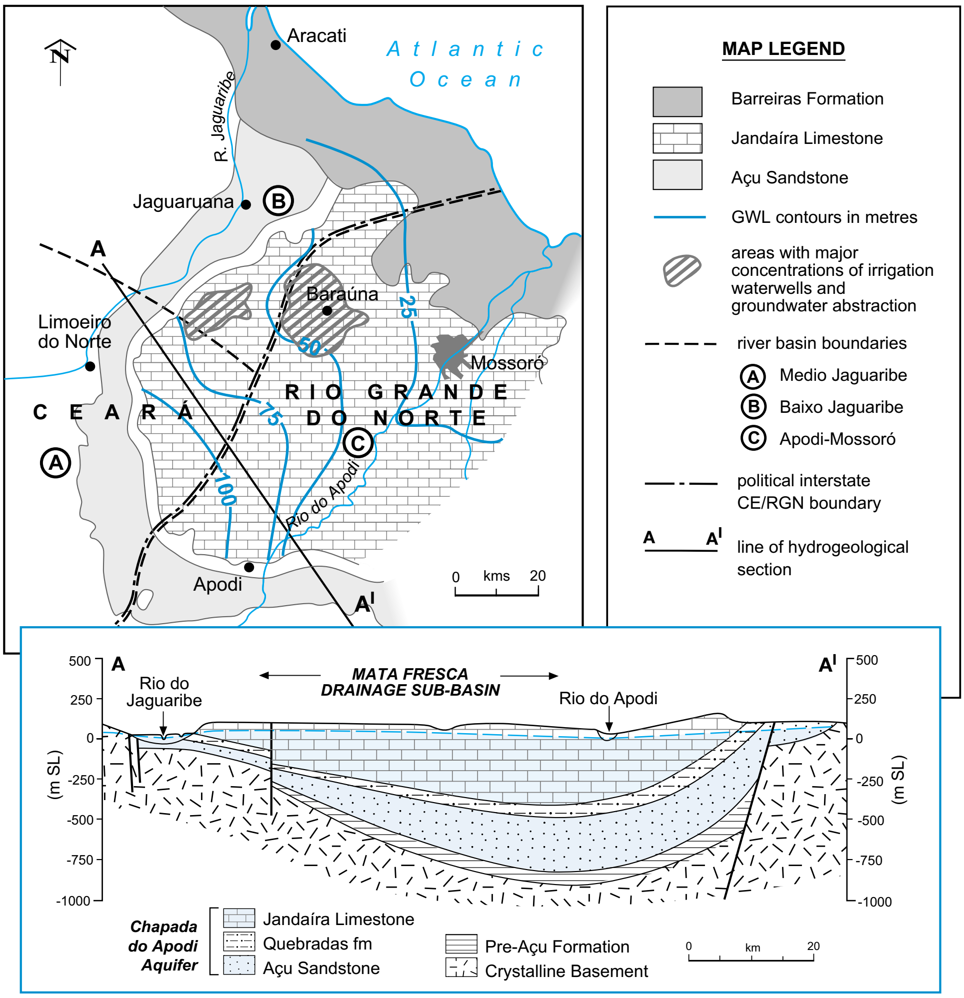
The main aquifer developed for irrigation use is the Jandaira Limestone of Cretaceous age, which outcrops across most of the Chapada do Apodi (a slightly elevated coastal plateau 80-140 m ASL between the Jaguaribe and Apodi rivers). It quite widely provides waterwells of 60-150m depth with yields of 10-60 l/s, but exhibits marked variation from massive karstified limestones to bioclastic calcareous deposits with much less cementation and to thinly-bedded marls with relatively poor waterwell yield potential. However, potential failure of irrigation waterwells and karstic land collapse due to water-table falls of 20-30m has given rise to serious sustainability concerns because:

- the rainfall is highly erratic with major episodes in just a few months each decade (eg : more than 700mm in January 2004), which account for most of the 'average rainfall' and almost all groundwater recharge
- the only other source of groundwater recharge is surface water irrigation returns (via canal seepage and field infiltration) from some 2,500 ha irrigated by the Jaguaribe-Apodi transfer scheme (constructed in 1987), which has progressively reduced due to introduction of canal lining and drip irrigation
- the limestone aquifer is of relatively limited storage, and the high transmissivity and karstic features may lead to rapid outflow of the periodic recharge.

The Jandaira Limestone is underlain by the Acu Sandstone aquifer (also of Cretaceous age, but of much lower transmissivity and higher storage), but is separated from it by an aquitard (the Quebradas Formation), which is of low permeability and sufficiently continuous to make the former hydraulically-independent, except for some limited leakage and the fact that some waterwells exploit both simultaneously. Natural groundwater quality in the Jandaira Limestone is good, with an EC of 1,000-3,000 uS/cm but relatively high $CaHCO_3$ hardness (giving some encrustation problems for irrigation equipment), although more saline water is locally encountered. An anomaly appears to be elevated lead concentrations (> 0.15 mg/l) and quality is also impacted (due to extremely high pollution vulnerability) by leaching of nutrients and some pesticides from agricultural soils (nitrate usually 50-70 mg/l). By comparison the Acu Sandstone is much more protected and generally has lower EC groundwater.

Groundwater use has been surveyed progressively since 2002, with detailed investigation during 2008-09 consolidating the picture. In the main exploitation area (known as the Mata Fresca Sub-Catchment) there were found to be 938 operating waterwells (only 2% of which extract from the Acu Sandstone), with an estimated abstraction of 289 Mm^3/a from the Jandaira Limestone and 13 Mm^3/a from the Acu Sandstone. The former considerably exceeds the average recharge over 9-in-10 years, but this increases to 544 Mm^3/a and 21 Mm^3/a respectively if exceptional rainfall months are included in the calculation. Most of the groundwater abstraction is concentrated in the hands of 10 or so major users (who operate some 160 high-yielding waterwells) mostly for irrigated fruit and intensive livestock production. There is only one large groundwater abstraction for public water-supply (the 13 deep waterwells in the Acu Sandstone supplying about 400 l/s to Mossoro) – the total public water-supply demand in the area totaling only around 1,250 l/s with Limoeiro do Norte and Aracati also having significant use.

The major groundwater management challenges being addressed are :



- controlling groundwater use in intensively-abstracted zones susceptible to drought waterwell yield failure through the identification of sub-zones where constraints on use should be applied pending further monitoring
- providing unpolluted groundwater for public/domestic water-supply across the Jandaira Limestone area, which exhibits extreme vulnerability to diffuse pollution from agricultural land-use practices – here solutions include deeper waterwells into the Acu Sandstone, establishing appropriate protection zones around Jandaira Limestone waterwells or bottled drinking water for small communities.

The main institutional needs to make sustainable groundwater management possible are:

- implementing agreed drilling and abstraction regulations, waterwell regularization (based on well inventories and user profiles), and harmonized monitoring, as well as groundwater use fees, through the standing inter-state working group (constituted following the first Inter-State Meeting on Shared Apodi Aquifer Management held in Mossoro on 11 November 2004 on the advice of GW•MATE and helped by ANA
- establishing a coordinated and participatory Information & Communication System, including both technical information (resource status, trends and vulnerabilities) and a guide to the complex network of groundwater users and other stakeholders involved – to facilitate acceptance of the required groundwater abstraction controls and to ensure that the SEMARH-RN temporary waterwell drilling ban from late 2002 in the Barauna District are sustained and extended as necessary
- strengthening institutional groundwater management capacity and user organization in both States.

Box C (2009)

ADDRESSING NON-BENEFICIAL EVAPORATION AND GROUNDWATER OVERDRAFT IN GUANTAO COUNTY OF THE NORTH CHINA PLAIN

Guantao County occupies 456 km^2 of the North China Plain of which about 39,000 ha are in irrigated cultivation and dedicated to staple grain production (winter wheat and summer maize, and some decreasing cotton cultivation). The population of the County is about 285,000 with 40% concentrated in Guantao City. It is known as the 'Golden Egg County' because 40% of its income is from poultry operations, using maize and wheat for feed. Traditionally irrigation demand for winter wheat was around 300 mm/a, compared to 160 mm/a for summer-maize. Industrialization is also now occurring, together with the important investments in glasshouse vegetable cultivation.

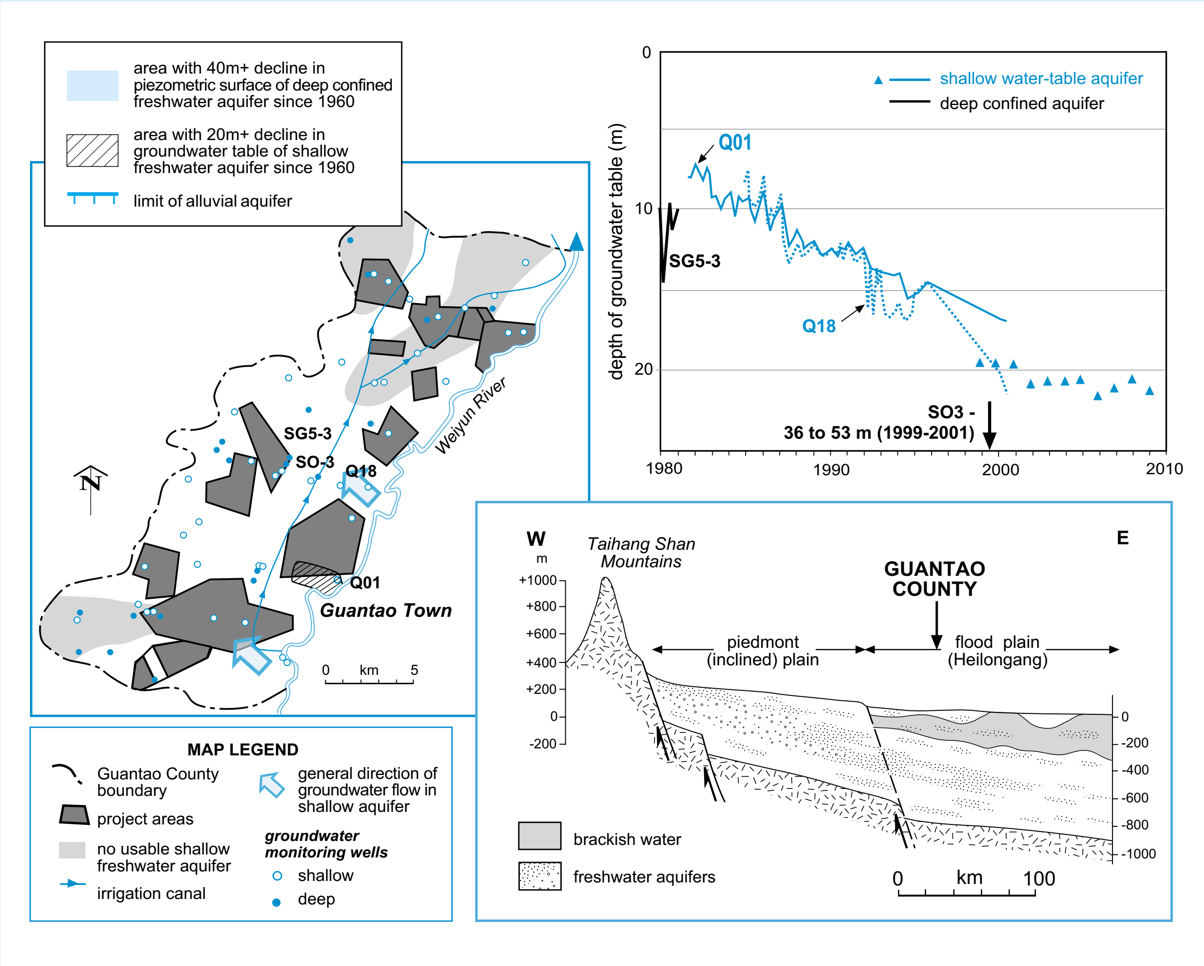
The County is underlain by a thick sequence of Quaternary sediments which form :

- a shallow silt-sand aquifer to 50-80m depth yielding 5-10 l/s to waterwells (mainly with TDS < 2,000 mg/l) – currently the saturated thickness is typically 20-30 m, although locally has reduced almost to zero
- a deeper semi-confined sandy aquifer giving larger waterwell yields (20-30 l/s), which occurs from a depth of 120-200 m onwards, and initially exhibited artesian overflowing groundwater.

These two aquifers are separated by a leaky aquitard containing brackish groundwater (TDS of 5,000-10,000 mg/l) whose base has moved downward by 18m on average during past 20 years due to deep groundwater extraction. Natural recharge to the shallow aquifer results from excess summer rainfall (average precipitation only about 530 mm/a), and also by limited seepage from the Weiyun River and associated Weixi Canal – but some recharge enhancement is also achieved through field dykes to impound and infiltrate summer run-off (June to September), seepage from artificial ponds and spate irrigation.

In the 1960s reservoirs in upstream hills were used to regulate local rivers to maintain irrigation canal flows, but much of their water resources were subsequently diverted to the major cities for urban and industrial expansion – and farmers were encouraged to develop waterwells to supplement or replace canal-water supplies. The explosion in groundwater abstraction for irrigation, and the loss of aquifer recharge due to diversion of riverflows and reduction in riverbed infiltration, led to a general decline of the shallow water-table from 7m to 20m bgl, and of the piezometric surface of the confined aquifer to 35-50m bgl, during 1980-2000. By 2005 there were 332 licenses issued for groundwater abstraction (following on the Chinese Water Law of 1988) and these totalled 91 Mm^3/a (irrigation accounting for 85%, industry for 7% and domestic use 8%), but actual withdrawals were thought to be 117 Mm^3/a with significant excess pumping by irrigation and domestic users. Of the total groundwater abstraction less than 5% was from the deep confined aquifer.

During 2001-06 the North China Plain—Water Conservation Project (WCP-1) financed agronomic, engineering and administrative measures to effect real water-saving measures on about 30% of the land area to reduce ET during the winter-wheat cycle, whilst not impacting and perhaps improving average crop yield to 300+ kg/ha. In practice such measures are believed to have been introduced on larger areas through community and private initiative. In parallel real-time monitoring of actual ET was undertaken from periodic satellite SEBAL thermal energy images, and groundwater level and quality monitoring was intensified. By 2009 real water-saving measures had been extensively practiced in the County for 6 years and the average county-wide actual ET is estimated to have been reduced to 575 mm/a, which represented an overall reduction of around 40 mm/a comprising savings from agronomic and engineering measures (12 mm/a), irrigation management through rainfall forecasting (20 mm/a) and reduction in cultivated area (8 mm/a). This has resulted in a reduction in the average rate of groundwater decline from about 0.70 m/a to 0.16 m/a (with groundwater abstraction having reduced from 117 Mm^3/a to 88 Mm^3/a – albeit with some annual variability between wetter and drier years) – and reducing irrigation applications on winter wheat from 4-5 to 2-3 per crop has also generated a 40-50% saving in electrical energy.



Guantao County Water Resources Bureau coordinated WCP-1 and is involved in the preparation of WCP-2 in an effort to replicate and up-scale the positive experience described over larger areas, but the following issues need to be clarified:

- some inconsistencies in ET, water-table decline and crop productivity/farmer income shown through WCP-1
- monitoring of 'with project' and 'without project' areas in equivalent hydrogeological conditions
- the level of reduction in abstraction from the deeper aquifer in view of the environmental hazard
- what has happened to urban and industrial groundwater abstraction, bearing in mind the need for increase

Further monitoring must also be included in WCP-2, in addition to consolidating the permanent real-time monitoring and assessment of real water-saving measures.

The following institutional questions must also be dealt with in WCP-2 as a matter of priority :

- By when the widespread introduction of water-saving measures will be accompanied by a corresponding reduction in groundwater use permits reflecting new consumptive use levels?
- What has been the effect of the much-publicized transfer of irrigation waterwells to private operation?
- Can the 'water credit-card' system of pump operation to control groundwater abstraction (already being used in the Hei He Basin) be introduced on communally-operated irrigation waterwells in Guantao County?

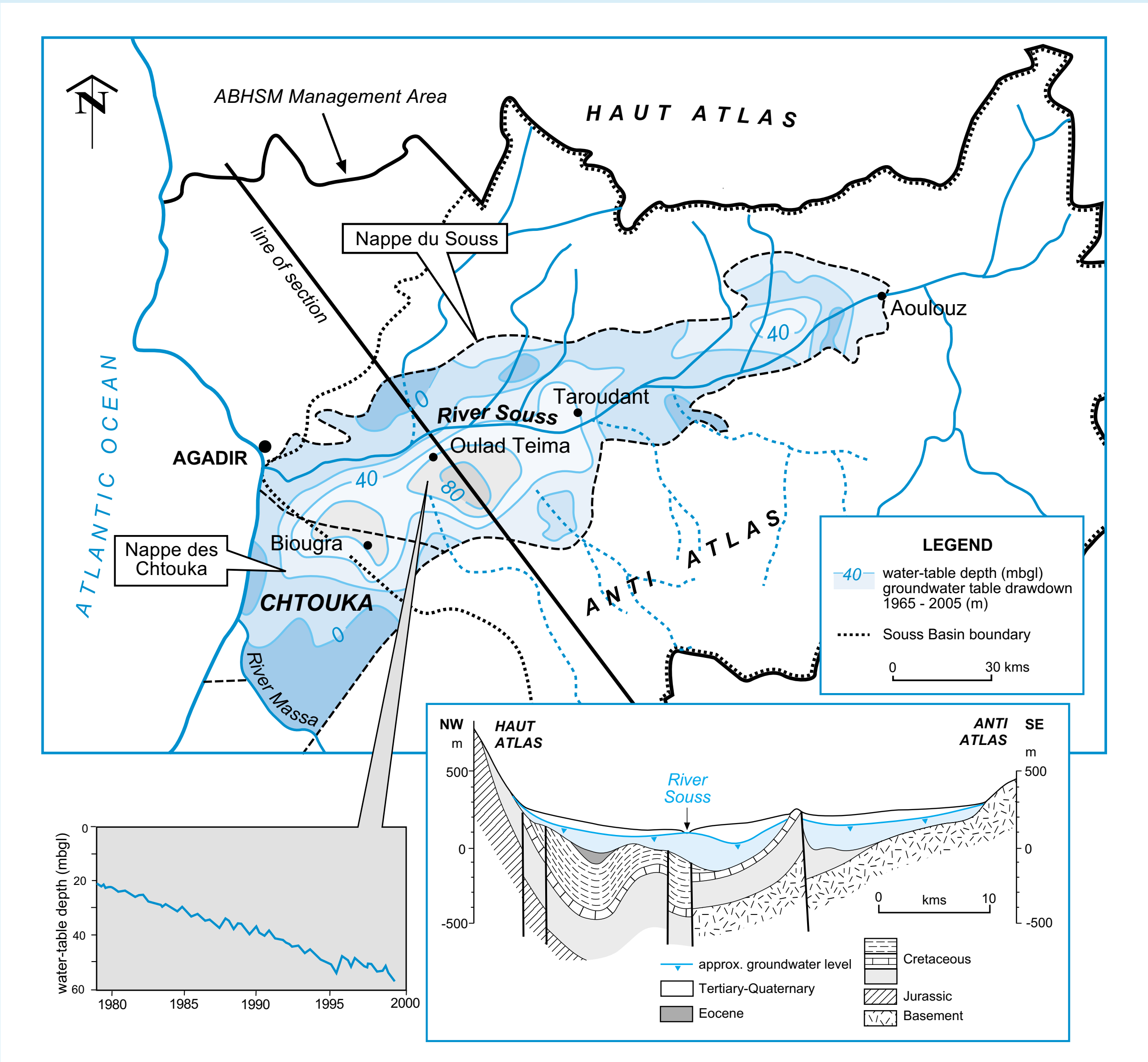
But the key challenge will be whether the strong national, provincial and county level government lead in groundwater resource management can be balanced with adequate community involvement through Groundwater User Associations, incorporating a wider range of stakeholders interests (industrial and domestic water-supply).

Box D (2009)

IMPLEMENTING A GROUNDWATER MANAGEMENT ACTION PLAN TO ADDRESS EXCESSIVE EXPLOITATION OF THE SOUSS-CHTOUKA BASIN IN MOROCCO

The aquifer system comprises a Tertiary–Quaternary sequence of weakly-cemented sediments up to 200m thickness, extending over nearly 5,000 km^2 across the Sousse River from the foothills of the Haut Atlas to those of the Anti Atlas. Away from the narrow Quaternary channel close to the Sousse River the aquifer deposits are only moderately permeable, but in the Chtouka area there is a transition mainly into permeable dune sands with some limestone. Average rainfall is less than 200 mm/a and there is only limited surface water runoff from a restricted area of the Haut Atlas, with natural groundwater flow generally parallel to the Souss River valley (except in the Chtouka area).

Agricultural irrigation is the predominant groundwater user, making up 95% of the total and amounting to 645 Mm^3/a – the irrigated crops being citrus fruits and significant areas of export-quality vegetables. Only a minor proportion of groundwater use (35 Mm^3/a) is for public water-supply – in part for Greater Agadir and for the smaller towns along the Souss valley. Since total recharge is estimated to be about 425 Mm^3/a, the current groundwater overdraft is some



MANAGEMENT ACTION PLAN		**2009-2012** *prevent growth of deficit (stop extension of irrigated area)*	**2013-2018** *reduce deficit noticeably (with 'real water savings')*	**2019-2030** *reduce deficit noticeably (reduce irrigated area)*
PRE-REQUISITIES	**Socio-Economic**	- assess 'winners and losers' - agree on sustainable and transition scenarios	- assess social impact - start action for lower water-use economy	- assess social impact - consolidate lower water-use economy
	Technical	- meter large abstractors - assess monitoring needs - initiate recharge studies and real water-saving research	- meter all users - improve monitoring - follow research recommendations - assess aquifer vulnerability	- optimize direct/indirect metering - full aquifer and abstraction monitoring
	Organization & Communication	- strengthen ABH and inter-institutional law enforcement - identify all stakeholders - sign Contrat de Nappe (CN 1)	- user, ABH staff/partner training - improve agricultural support - sign Contrat de Nappe (CN 2) - establish/consolidate AMOR and ensure ABH 'lighthouse function'	
MEASURES	**Regulatory ('Stick')**	- constrain waterwell drilling - increase finance for water police - condition agricultural support to waterwell regulation	- conclude regulation for larger users and protect smaller users - further improve enforcement	- consolidate enforcement - implement quality protection - publicize offences and sanction offenders
	Supply & Demand Side Management ('Carrot')	- negotiate and construct recharge enhancement works (but only if cost effective and socially beneficial)	- support 'real water savings' through appropriate irrigation technology improvement	- set-up compensation for irrigated area reduction - support establishment of lower water-use economy

255 Mm^3/a (discounting any natural discharge) and water-table depletion has reached 80m in some sectors – with increasing pumping costs, saline intrusion in the coastal area and abandonment of some agricultural land.

Exploitable groundwater reserves (those economical for current uses) can be pumped from up to about 150m and are estimated to be some 18,000 Mm^3 – which is a useful indicator of the scope and time available for 'adaptive management'. But uncertainties remain in respect of the following components of the groundwater balance :

- active recharge from irrigation returns, reducing with the spread of pressurized drip-technology
- the extent of non-beneficial evaporation from natural vegetation and irrigation practices.

But there is a pressing need to implement a groundwater demand management strategy using available information, which can be refined subsequently.

The ABHSM (river basin management agency) has taken the initiative on stakeholder participation through a 'Contrat de Nappe' – and prepared (with assistance of GW•MATE) a staged long-term Groundwater Management Plan to counteract negative social and environmental prejudice, aimed at groundwater table stabilization during a specified period (using aquifer reserves in the meantime). The core of the Plan is the simultaneous implementation of 'carrot and stick' measures (regulation with economic incentive), together with socioeconomic, technical, organizational and communication actions. To make the implementation of this Plan feasible the following support measures will be needed :

- strengthening ABHSM, particularly in respect of 'water police' to enforce controls on waterwell drilling, abstraction and irrigated area, and to collect groundwater resource fees – thereby promoting regulatory measures with economic incentives to increase irrigation efficiency
- establishing an Aquifer Management Organization with representation of all groundwater users and other stakeholders
- streamlining regulations to implement the new Water Law, which is considered to be up to international best practice.

Box E (2009)

PROMISING COMMUNITY ACTION ON GROUNDWATER MANAGEMENT IN THE WEATHERED HARD-ROCK AQUIFERS OF PENINSULAR INDIA

In Peninsular India approaches to groundwater management must take account of the following:

- the extremely large number of individually small users
- limited institutional capacity for resource management (needing to be focused on the few critical aquifers of major potential which are at risk of irreversible degradation)
- characteristics of the predominant hard-rock aquifers, which mean that pumping drawdown effects are localized (restricted to the immediate micro-watershed and in many cases village panchayat area) – ignoring for the moment the effects of diffuse stream baseflow diminution
- groundwater table depletion will not be accompanied by irreversible aquifer side-effects and/or environmental degradation (although troublesome fluoride concentrations may arise).

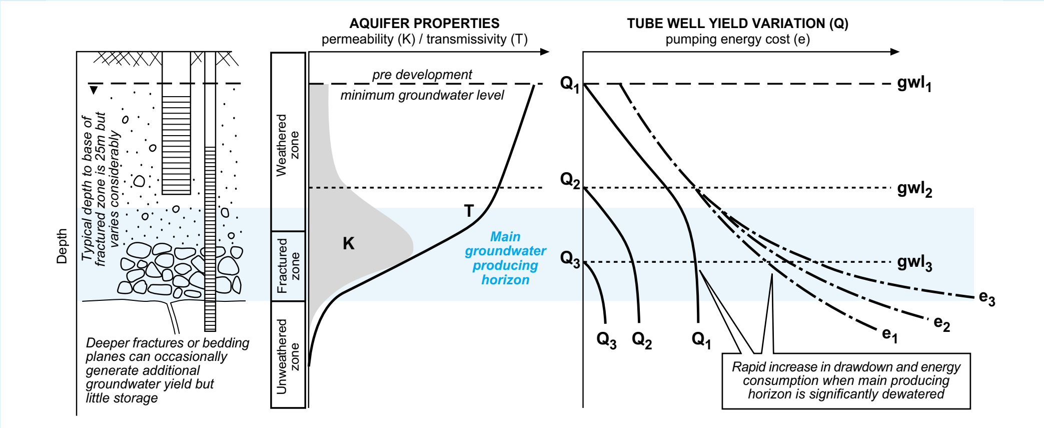
Thus community self-regulation of groundwater use is favoured as the most realistic option – and there are important examples of this approach in both Maharashtra and Andhra Pradesh.

Hivre Bazar (a village of 1,200 population and 975ha area) in the elevated drought-prone Deccan Traps country of Maharashtra (450 mm/a average rainfall) is a well-established example. Here the weathered zone of the Deccan Traps Basalt reaches to about 12-15 m bgl and is underlain by massive (sparingly fractured) basalt providing only very limited additional groundwater flow. Under leadership of an informed and charismatic Village Council Chief, a concerted effort on groundwater management commenced in 1994 (as part of the Maharashtra Ideal Village Social Development Scheme) with implementation of a comprehensive 5-year plan, following a long history of drought propensity and land degradation – with farmers struggling to maintain a kharif crop and feed their families and cattle without leaving the village periodically to search for paid work.

In Hivre Bazar staple crops are grown primarily for home consumption with residues serving as livestock fodder or domestic fuel, while most pulses, onions, vegetables and flowers are sold at market. In the most favorable years almost 60% of the land can be irrigated, but in drought rabi wheat and jayaad (summer) crops have to be radically reduced. The main groundwater-related decisions of the Village Council (on its Chief's advice) during the mid-1990s were :

- most critically, prohibiting the use of borewells (and the drilling of vertical bores in dugwells) for agricultural irrigation – which had the great benefit of moving farmers' minds and resources away from 'competition for deeper groundwater' to 'cooperation on maximizing benefits from groundwater to which they nearly all had access'
- subjecting the micro-watershed to comprehensive reforestation and water harvesting - notably hill contour-trenching, Nalla stream bunds, prohibiting axe use (dung replacing timber for domestic heating) and a livestock grazing ban (with scythes hired to hand-cut fodder for animal stall feeding)
- banning sugar-cane cultivation (given its high water-use and other implications).

Most importantly also, village-level crop-water budgeting was introduced in 2002 – the post-monsoon availability of soil-water and groundwater being estimated from field data, human and livestock water needs given first priority, and then (using previous experience) the amount available for irrigated cultivation is calculated and compared to the aggregate need of villagers' proposed cropping – and in dry years villagers are asked to reduce their proposed irrigated area and to give preference to low-water demand crops, with mutual surveillance usually being enough to achieve compliance. Such proactive groundwater management has resulted in a marked contrast between Hivre Bazar and most surrounding villages. As many as 32 dugwells produce important revenue in the jayaad season from irrigated onion, vegetable and flower cultivation, and only a few in the upper watershed dry-out – with the 'household-level benefits' of community land and water management resulting in household incomes rising markedly (to over US$500/a on average) and land-values appreciating many-fold in the past 15 years.



Andhra Pradesh is mainly underlain by granitic basement rocks, which have been fractured and decomposed by repeated cycles of tropical weathering to create a shallow 'low-storage' aquifer system annually recharged to varying degree by monsoon rain. In its most favorable typology the groundwater body has 15-25m thickness along lineaments below topographic lows thinning on higher ground, but elsewhere more schistose bedrock leads to groundwater bodies which are more patchy and thin. Most 'natural groundwater flow' is concentrated in a 5m or so horizon at the interface between the weathered and fractured zones. Average rainfall totals 650-950 mm/a, but is highly concentrated in a single monsoon season (June-August) during which 'natural recharge rates' are believed to average 70-100 mm/a. In contrast by the late 1990s groundwater extraction rates had grown to an equivalent of 120-150 mm/a (curiously almost regardless of waterwell densities, given that the entire area is heavily populated and cultivated). Groundwater is exploited by dugwells penetrating to just below the weathered zone and borewells mainly from 30-50 m deep (of variable yield but with 60% achieving >2 l/s). During the past 30 years the number of dugwells has remained at about 0.9 million but, with an increasingly large portion falling dry or becoming 'seasonal', there has been rapid growth in the number of borewells to the current estimate of 1.7 million (with average depths steadily increasing). But this massive expansion of groundwater use has had serious impacts :

- widespread excessive exploitation of available resources with serious dewatering of the main water-bearing horizons of the shallow aquifer system
- inefficient borewell pumping practices (related to 'flat-rate rural electricity tariff') with farmers continuing to operate pumps at far too deep groundwater levels, causing large well entry/pump friction losses, and leaving pumps switched-on to obtain a supply when the (discontinuous) power activates.

The pioneering APWELL Programme of the 1990s covered some 14,500 marginal farmers using 14,000ha of irrigated land in 370 villages in most of drought-prone Andhra Pradesh. It developed participatory hydrological monitoring to provide farmers with the necessary knowledge, data and skills to understand groundwater resources and to manage their use through controlling on-farm demand for water, without offering any cash incentives or subsidies. The subsequent APFAMGS Programme, which commenced in 2007, makes the strong link between groundwater availability and irrigation use but leaves farmers free to make crop planting decisions and extract groundwater as they desire. Nevertheless, in a majority of pilot project areas the results have been very positive as witnessed by :

- reduction in groundwater use through crop diversification and irrigation water-saving techniques – with 42% of areas consistently reducing the rabi groundwater overdraft over 3 years and a further 51% achieving intermittent reductions
- farmers improving profitability despite less water-use – with the reduction in groundwater overdraft coming from multiple individual risk-management decisions rather than 'altruistic collective action'.

The up-scaling and replication of this very positive experience will necessitate a flexible phased approach which engages experienced support organizations, together with development of a 'lighthouse function' in the State Groundwater Department to monitor the process and to ensure continuity and momentum.

Box F (2008)

OPTIMIZING GROUNDWATER USE FOR IRRIGATION OF STAPLE CROPS ON PART OF THE GANGETIC PLAIN IN UTTAR PRADESH, INDIA

The vast alluvial tracts of the Gangetic Plain are underlain by an extensive thick aquifer system, which represents one of the largest groundwater storage reservoirs in the world. This aquifer system offers generally good waterwell yield potential (even to tubewells of only moderate depth) and is recharged directly from infiltrating monsoon rainfall 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 of farmers experiencing inadequate or unreliable service from canal irrigation systems and widely represents as a large proportion of total irrigation water-supply. It shows great potential as an adaptation strategy for climate change scenarios which predict progressive reduction of Himalayan glaciers and of associated river baseflows. But the alluvial sedimentary aquifer can contain saline water horizons and/or salinization due to phreatic evaporation which considerably complicate sustainable groundwater resource exploitation.

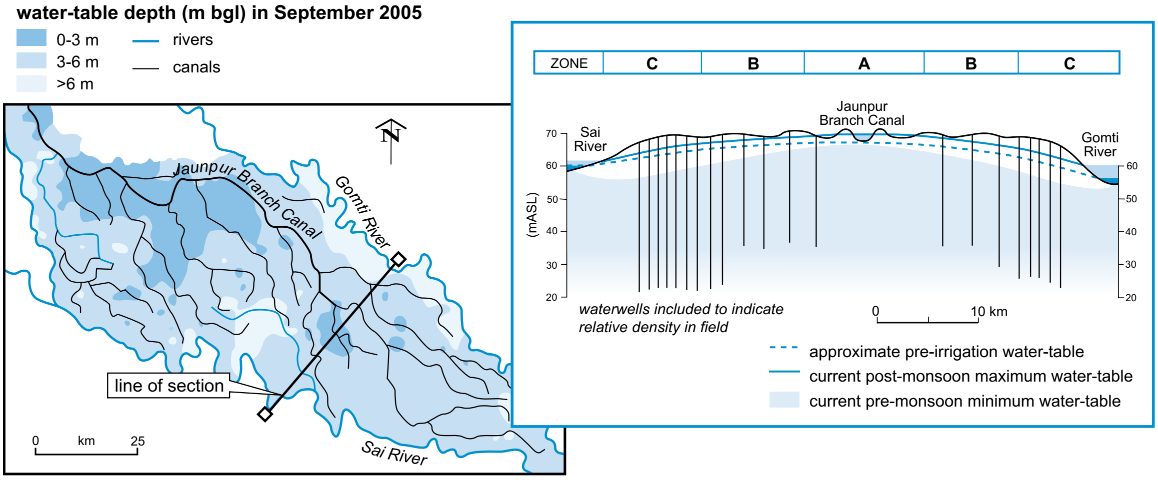
The main kharif (hot wet season) and rabi (cool dry season) crops are paddy rice and winter wheat respectively, accounting for around 70% of all crops grown, although sugar-cane can locally reach 40% in irrigation canal head-water zones. Groundwater use has widely increased to represent as much as 70% of overall irrigation water-supply despite limited coverage of rural electrification and dependence on diesel-engined pumps. With the recent increases of hydrocarbon fuel prices, groundwater users have been paying US$100-150/ha for pumping groundwater as opposed to US$5/ha for (highly-subsidized) 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 salinization 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, between the Ghagara and Gomti Rivers in central Uttar Pradesh. Integrated numerical modelling (of crops, soil, canal and aquifer) based on excellent field data clearly shows that more 'optimized 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 1.4 to around 2.2, 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.

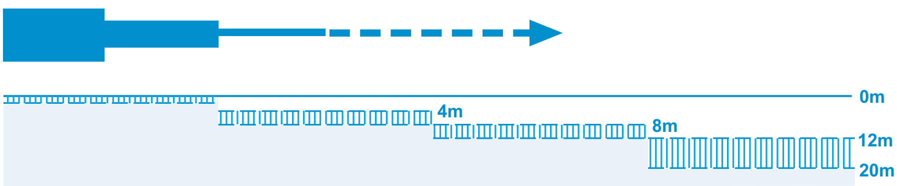
And most importantly, pursuing an appropriate management action plan in which the land surface has been sub-divided on the basis of hydrogeologic and agroeconomic criteria into a number of small 'micro-management zones', with specification of measures required for efficient and sustainable conjunctive use. 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.



CANAL REACH (or) ECO-HYDRO-AGRO ZONE	COMMAND AREA (see section above)			NON-COMMAND AREA
	A : HEAD	B : MID	C : TAIL	

PRESENT IRRIGATION CANAL FLOW (relative volume & reliability)

PRESENT GROUNDWATER TABLE LEVEL (pre and post-monsoon)



	A : HEAD	B : MID	C : TAIL	NON-COMMAND AREA
IRRIGATION WATER SERVICE SITUATION	abundant with excessive offtakes and numerous canal breaches – reluctance to use groundwater	substantial canal water availability but unreliable delivery means most farmers also have to use waterwells	very intermittent and unreliable canal flow – total dependence on waterwells with diesel engined suction pumps.	total dependence on waterwells – but relatively good irrigation practices and water productivity
GROUNDWATER RESOURCE STATUS	**water table too shallow and in some cases rising – causing serious land loss through soil water-logging and salinization**	shallow but tolerable water-table fluctuations – although increase in canal flows could change the picture	**water-table still declining - questions sustainability of suction-lift pumps**	water-table relatively deep and still declining with consequent need to move to electric submersible pumps
GROUNDWATER MANAGEMENT NEEDS	stimulate groundwater use (to substitute for canal water) to improve soil drainage and ameliorate salinization.	**careful monitoring needed to detect any rising water table when canal water availability improves**	target water-table stabilization through improved canal water availability and reducing irrigated area	**target water-table stabilization by reducing irrigated area but growing higher-value crops**

The promotion of more planned 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.

Box G (2009)

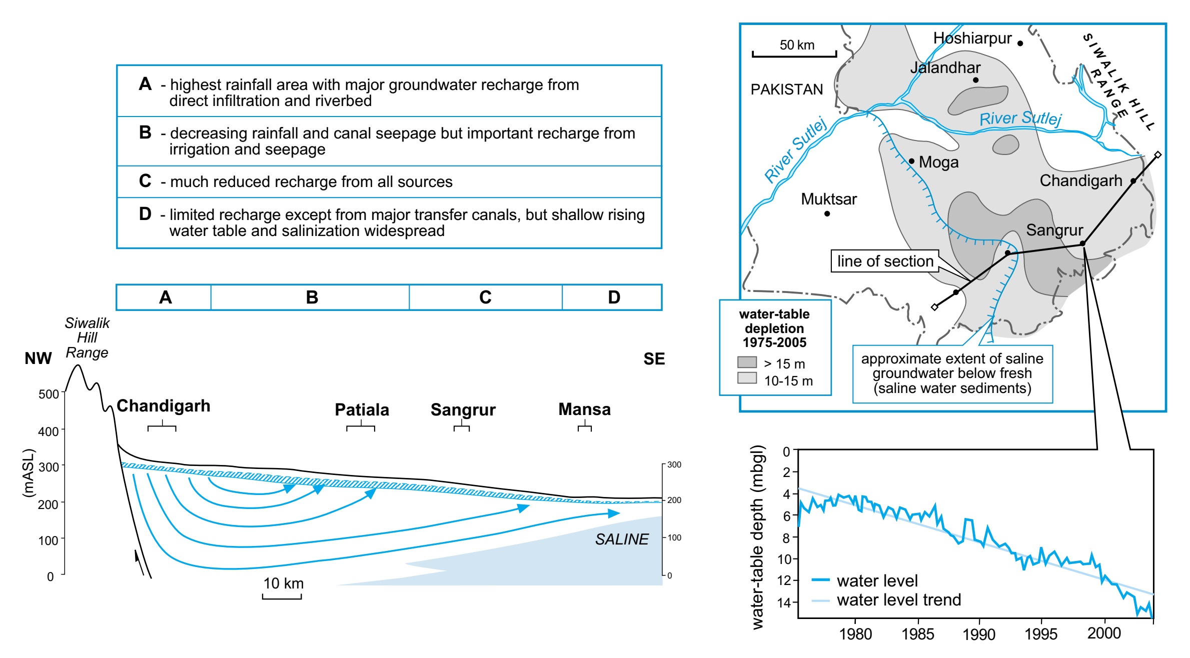
CONFRONTING EXCESSIVE GROUNDWATER USE FOR IRRIGATION OF STAPLE CROPS ON THE INDUS PENEPLAIN OF CENTRAL PUNJAB, INDIA

The central part of Punjab State provides an important example of a successful 'state policy approach' to address excessive groundwater exploitation – and relates to the elevated alluvial areas of the Indo-Gangetic Peneplain, where water tables are relatively deep and coverage of irrigation canals is not all that extensive. The Punjab was a showcase for the so-called 'green revolution' – with the modernisation of agricultural techniques, allied to fertile soils and industrious farmers transforming the State into 'India's grain basket' such that almost 90% of its land area is used for (hot wet season) kharif rice and (cool dry season) rabiwheat. Today Punjab State provides about 20% and 11% respectively of national wheat and rice production from only 1.5% of the national land area, and since the 1980s has seen a major increase of the area under double-cropping and of crop yields per unit area – with the average cropping intensity reaching 1.9.

A major part of this agricultural success has been based upon the use of groundwater for irrigation – and the number of operating tubewells has increased from 0.5 million in the 1970s to 2.3 million in 2008. Some 70% of the area now under irrigated cultivation is dependent on groundwater, since the surface-water canals can only meet a minor proportion of current agricultural demand. The consequences of this massive and uncontrolled development of groundwater is that the water-table has been widely in continuous decline, with depletion rates currently in the range 0.6–1.0 m/a (equivalent to a net overall rate of excessive abstraction in the range 120–180 mm/a), except in the down-gradient saline groundwater zones.

Over most (but not all) of Punjab the alluvial outwash aquifer system is relatively thick (>150m), and while this storage depletion is in itself not critical (being partly an inevitable significant consequence of groundwater development), it is resulting in mounting cumulative cost for :

- State Government, which underwrites most of the cost of rural electrical energy provision (apart from a small annual fixed charge paid by farmers), in a situation where consumption is currently increasing at around 5%/a at a time when unit energy prices are generally rising and additional generating capacity is difficult to earmark



- farmers, who are being confronted with the need to move from low-cost waterwells equipped with surface-mounted centrifugal pumps (costing less than US$ 500 each) to deeper tubewells with electric submersible pumps (costing more than US$ 2,500 each) – resulting in adverse impacts on those farming least land

Elsewhere, however, the aquifer contains layers of saline groundwater which is being mobilized as a result of excessive pumping and in the vicinity of important towns much more accentuated rates of aquifer depletion are currently occurring because of competition for available groundwater resources between urban utilities and agricultural irrigation. For all of these reasons there is an urgent need to find ways of stabilizing the groundwater table (and even of inducing a partial recovery) – providing that this does not constrain farming production too severely. While an array of interventions are likely to be needed in the longer run to reduce groundwater use to sustainable limits, certain 'technical demand management interventions' related to paddy-rice cultivation (by far-and-away the largest consumer of groundwater resources) were identified that could be implemented immediately to good effect.

In 2008, a State Government Ordinance was issued prohibiting transplanting of paddy-rice until June 10 (the onset of monsoonal rain and 35-40 days later than normal), because agronomists identified that evaporation rates from paddy during this period were very high and there was potential for making a 'real water-resource saving' (by eliminating essentially non-beneficial evaporation) totaling more than 90mm without necessarily impacting on crop yields – although this presented some complications for farmers in terms of labour availability for planting-out seedlings. The expected water resource saving was equivalent to 50-65% of the groundwater overdraft and that of electrical energy statewide amounted to 175 million kWh. The measure was highly successful because :

- there was limited farmer resistance – because yields were not negatively impacted
- compliance was more than 95%, – because any violations were highly visible and severely sanctioned (fine of US$200/ha plus uprooting of crop)
- once a critical mass agreed to delay transplanting, farmers who did not comply also faced an increased threat of pest infestation.

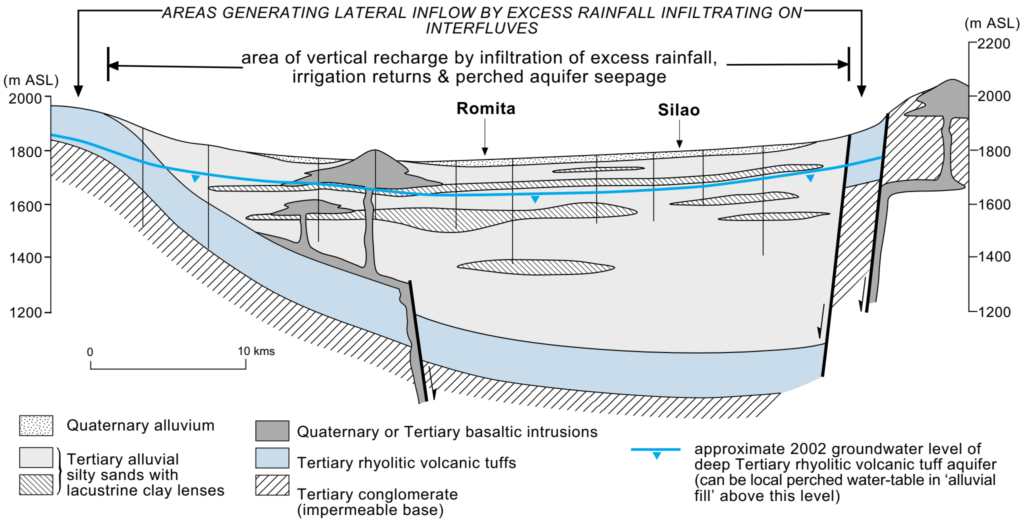
Given the success this measure was incorporated into the Punjab Preservation of Sub-Soil Water Act of 2009, and the State Government is also considering additional measures, such as laser-levelling of fields, soil moisture-based irrigation timing for winter wheat and shorter-duration rice varieties (with 15 days less gestation) – all aimed at increasing crop water-productivity and reducing non-beneficial evaporation so as to eliminate the current groundwater 'irrigation overdraft'. Although field data are not yet available on the water-table response to these interventions, preliminary information confirms major water-saving potential. Thus the Indian Punjab represents a case where reducing consumptive use of a 'major water-intensive crop' through a state-level policy change translated directly into lower groundwater abstractions, in part because there are no other significant unrealized water demands from the agricultural sector and no negative impacts on crop yield.

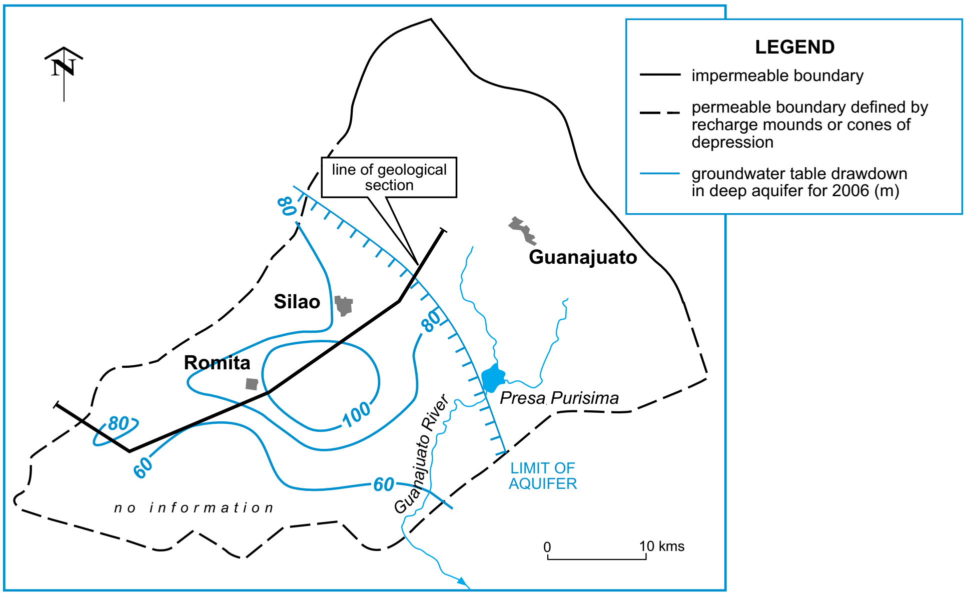
Now that this demand-management intervention has been repeated for a few years, it is essential to monitor closely the aquifer water-level response and to check that other components of the groundwater balance are not experiencing any parallel changes. In this context it is very important to appreciate that while over 70% of the irrigation water-supply is derived from tubewells, as much as 35% of total groundwater recharge is linked with seepage from the extensive (but inefficient) irrigation canal system. If this seepage were reduced by engineering measures (such as canal lining) with the intention of diverting water to demands in other areas, the effect on the local groundwater resources would be very negative.

Box H (2007)

NEED FOR HIGH-LEVEL POLITICAL ACTION TO CONFRONT HARSH REALITY OF RESOURCE UNSUSTAINABILITY IN THE SILAO-ROMITA BASIN OF MEXICO

Guanajuato State in northern central Mexico is situated in the upper part of the Lerma-Chapala Basin in an area of elevated intermontane valleys receiving low seasonal rainfall. The State was traditionally one of livestock rearing, with important associated agro-industries such as milk production, leather processing and shoe manufacture. But from the 1950s, under strong federal government stimulus, it has witnessed major growth to a population of around 5.0 million and a broadening industrial base with construction of an oil refinery, petrochemical complex and a major thermoelectric electricity generating plant. By the early 1970s this had led to considerable stress on groundwater resources, reflected by an accelerated rate of waterwell drilling – and currently there are some 17,000 wells abstracting in the order of 4,000 Mm^3/a, which is estimated to be about 1,200 Mm^3/a above resource replenishment.





The hydrogeological conditions and groundwater resource status of the Silao-Romita area are typical of much of Guanajuato State – the aquifer system comprises a thick sequence of mainly Tertiary alluvial sediments interrupted by occasional lacustrine clays, overlying a more extensive rhyolite tuff which is intruded by Tertiary and Quaternary diabases and basalts. Prior to significant waterwell drilling, groundwater was encountered at shallow depth in a phreatic aquifer extending to 60 m bgl, but this was rapidly depleted by abstraction. Today the deeper part of the Tertiary alluvial deposits together with the underlying rhyolite tuff provide most groundwater to wells with static groundwater levels locally reaching 100m bgl, but perched water-tables occur above the more extensive lacustrine clays, especially in the surface-water irrigation area along the Guanajuato River. Groundwater resources are recharged by a number of different mechanisms :

- lateral subsurface inflow from neighboring interfluves, especially where these are formed by the outcrop of Tertiary rhyolites
- vertical recharge, directly from excess rainfall or indirectly from surface watercourses, together with returns from excess irrigation by either surface water or groundwater but the estimation of each presents significant uncertainty, and the existence of perched aquifers (intercepting or delaying part of the vertical recharge) further complicates the picture.

The main technical issue of concern to long-term aquifer management is the potentially erroneous evaluation of subsurface inflow and its relationship with aquifer storage being drained. The uncertainties cannot be resolved by short-term investigation, but must be borne in mind when interpreting the numerical groundwater model outputs and formulating related management strategy. Nevertheless, current best estimates suggest that present 'active groundwater recharge' is less than 20% of consumptive use and it is clear that this aquifer has for long been excessively abstracted – resulting in a history of long-term aquifer depletion and now to pumping lifts which threaten the viability of many types of irrigated agriculture. Thus the principal resource challenge is 'managing the depletion of groundwater reserves' through addressing the following issues :

- For how many more years will current groundwater abstraction be physically sustainable, given the aquifer characteristics ?
- Is the present economic productivity of groundwater high enough, given the largely non-renewable nature of groundwater resources ?
- How can the security of existing municipal water-supply wells be assured, and should there be a 'public buy-back' of some groundwater-irrigation use rights to ensure this priority use?

Clearly the implementation of 'exit strategy' from socioeconomic reliance on local groundwater resources requires both strict enforcement of legislation to ban the construction of new waterwells and ensuring compliance with substantially-reduced abstraction volumes through informed stakeholder participation. This could be achieved provided the following measures are taken :

- radically changing the approach of the civil-society Aquifer Management Committee (COTAS), which (enabled, financed and nurtured by State Government Water Agency (CEAG) since 1998) has been very successful in raising community awareness, promoting educational programs and watershed conservation measures but has not regarded aquifer stabilization as its main task
- devolving groundwater rights administration from the national to state level, and strengthening the COTAS to participate in this process, given that the National Water Commission (CONAGUA) has very limited local enforcement capacity
- CEAG must discuss openly the groundwater resource situation, and its effect on irrigated agriculture, with State Agriculture Agencies to reach agreement on basic reforms of agricultural policy to confront the harsh realities of groundwater resource depletion in the Silao-Romita Aquifer.

Box J (2010)

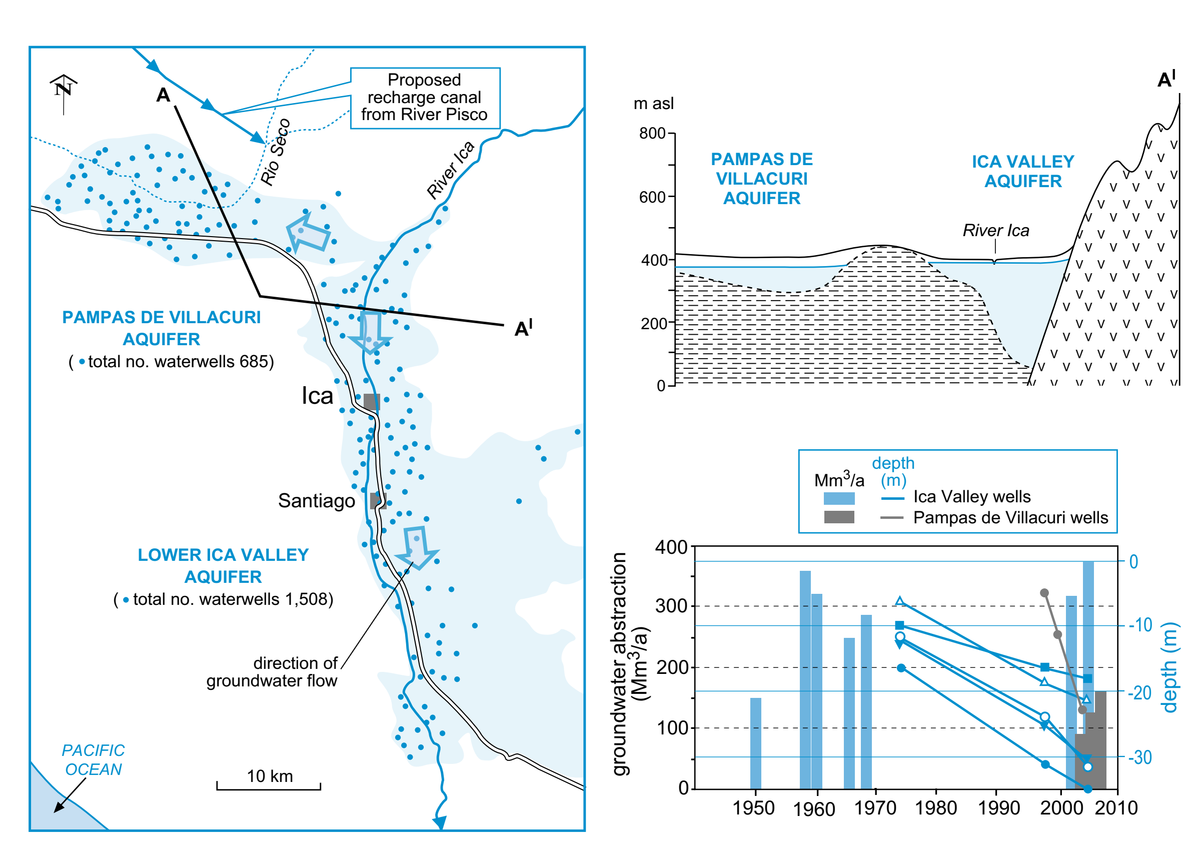
IMPROVING GROUNDWATER MANAGEMENT OF THE ICA AREA AQUIFERS OF COASTAL PERU FOR HIGH-VALUE IRRIGATED VEGETABLE PRODUCTION

The hyperarid Ica area (average rainfall <50mm/a) has two significant aquifer systems – one in the Lower Ica Valley and the other on the Pampas de Villacuri – while both feature in this case history and are partially connected, it is important to be clear that they have very distinct 'resource dynamics' and thus require different management approaches.

The Quaternary alluvial aquifer of the Lower Ica Valley is of considerable thickness (up to 200m saturated with the water-table generally at 10-60m depth), yields 20-60 l/s to waterwells, and receives continuous recharge directly and indirectly from the Ica River, through natural riverbed infiltration and by seepage from the irrigation infrastructure and field-level practices – and although vulnerable to upstream riverflow diversion or consumptive use it has large storage reserves to buffer their impacts and to permit adaptation to climate and economic change. Groundwater abstraction from this aquifer, conjunctively with surface-water canals, supported large-scale irrigation of cotton and grapes from the mid-1950s (with concern over falling water-table first voiced in the 1970s), but by the 1990s the irrigation infrastructure fell into decline. At this time the arrival of agricultural-export enterprises was welcomed by many smaller farmers, who sold their waterwells, groundwater and irrigated land – today about 30% of the irrigated area (totaling 19,000 ha) uses waterwells alone for double-cropping of export asparagus (requiring application of some 1,000-1,200 mm/crop).

The present rate of groundwater abstraction (370 Mm^3/a) is about 70% of total water use – using 820 waterwells out of an inventory total of 1750 and is concentrated in Santiago District (170 Mm^3/a). The groundwater table continues to decline at 0.2-0.6 m/a, with an accumulated fall of 10-20m since the 1970s. However, the detailed groundwater balance has undergone significant change – because 'spate irrigation' was formerly practised (in which fields were flooded during high riverflows to recharge the aquifer and to deposit sediment for soil improvement), but this has reduced with introduction of intensive vegetable cultivation utilizing pressurized drip ferti-irrigation techniques (which also increased consumptive use and have negligible returns to groundwater). Local authorities are now engaged with groundwater users in an effort to restore lost groundwater resources by reactivating irrigation canals and infiltration basins to enhance aquifer recharge from flood riverflows. The changing pattern of groundwater use and continued water-table decline strongly argue for a precautionary adaptive approach to resource management – with the local water-resources agency (ALA), in coordination with existing users, imposing constraint of new waterwell construction and changes to existing waterwell use, whilst the effectiveness of recharge enhancement is evaluated through detailed monitoring and modeling. Domestic water-supply needs must be prioritized by ensuring the security of the municipal (EMAPICA) waterwells in terms of both access and quality – with appropriate well deepening and/or protection measures taken.

In contrast most groundwater in the Pampas de Villacuri Aquifer (Rio Seco Irrigation District) is essentially a non-renewable resource, which mainly originated in a previous era of wetter climate, with only modest active subsurface inflow (65 Mm^3/a) from the main Ica Valley and very occasional recharge from any flash-flows in the 'Rio Seco quebradas'. Following private rural electrification in 1992, which drastically reduced pumping energy costs, some 550 irrigation waterwells had been constructed by 2007 bringing 13,200 ha of desert land into export-quality asparagus production using 185 Mm^3/a of groundwater (almost all of which represents consumptive use) – including 15 large-scale enterprises with more than 1,000 ha of irrigated land each. This has resulted in a groundwater table decline to around 25m bgl at rates of 1.0-2.5 m/a (with the base of the aquifer at 100-150m bgl) and a marked increase of groundwater salinity due to upconing from the underlying marine Pisco Formation (resulting in salinities of EC> 4,000 uS/cm which is impacting agricultural productivity). Physically-sustainable large-scale irrigation in this area (beyond a much-reduced hectarage) will be dependent upon the technical feasibility and economic viability of surface-water transfer and artificial recharge from periodic excess flows (averaging 110 Mm^3/a) in the Lower Pisco Valley some



15-20km to the north. Given the resource (quantity and quality) restrictions, regulatory action is imperative, and:

- in 2008 a waterwell drilling ban was ratified – but now requires full implementation with the public administration having enforcement capacity and being supported by user vigilation
- it will be necessary to reduce the depth of many waterwells (through cement plugging) to reduce the incidence of up-coning saline groundwater
- it will be important for both groundwater users and public administration to acknowledge the harsh reality of the fact that a significant part of current use is unsustainable and to identify an appropriate exit solution.

The ANA, World Bank–supported, water resources management initiative is resulting in intensive stakeholder consultation on the new Water Resources Act, and in GW•MATE assistance in strengthening groundwater management capability nationally and locally. This is setting the stage for implementing management on the ground, but requires the following urgent additional measures:

- 'groundwater champions' with supporting teams are established in ANA and the priority ALAs
- transferring to ANA resources from other government departments whose roles/responsibilities they are assuming
- strengthening the legal teams of the public administration to facilitate renegociation of groundwater use rights in the light of improved water resource assessments and changing use practices
- streamlining key procedures, such as improving the enforcement of groundwater abstraction bans through implementation of quality control/assurance (ISO-9001) standards
- providing adequate aquifer management operating budgets at national and local levels, removing bureaucratic restrictions on contracting appropriate staff and making provision for career development
- establishing an interactive ANA Information & Communication Unit to integrate the technical aspects into the complex stakeholder network, and to enhance synergy and prevent corruption.

GENERIC LESSONS OF GW•MATE EXPERIENCE

General Progress of 'Pilot Projects' and Other Initiatives

- All of the projects conducted and initiatives evaluated (**Boxes A-J**) have achieved useful progress in relation to the major challenge of groundwater resource sustainability – but the extent to which this has included marked reductions of consumptive irrigation water-use is variable (**Table 2**) and the level of success is a function of appropriate local institutional arrangements, adequate financial investments and a balanced mix of user incentives and constraints. Some of the cases presented are a definite source of inspiration for the future – but all also reveal vulnerabilities, primarily of a socioeconomic and institutional character, in relation to the continuity and replicability of the process (**Table 2**).

- In most cases (except **Box B** – the Apodi Aquifer System, Brasil and **Box J** – Ica Aquifers, Peru) evaluating the impact of irrigated agricultural practices on groundwater quality (and any threat to its function as the primary source of rural drinking-water) was outside the terms of reference of the pilot projects (being outside the competence of the national/provincial counterpart agency involved). However, in the longer run it will be essential to consider the quality dimension of groundwater management in areas of irrigated agriculture – noting that the most serious impacts are likely with intensification of agricultural production on thin permeable soils and that they can lag decades in becoming fully apparent given pollutant transport processes in most groundwater systems.

Pros and Contras of Individual Management Instruments

- In this chapter an appraisal of the pros and contras of individual groundwater resource management instruments and measures is made – whilst recognizing that a balanced package of actions and measures is normally required for success, rather than implementation of one instrument alone.

Groundwater Use Regulation and Charging

- An element of groundwater use regulation is generally required (including, where circumstances demand, banning the construction of new waterwells and capping the abstraction from existing ones) provided that the number of individual users is not such as to burden the local water resource agency with an impossible administrative task in relation to their capacity (which may mean that small users have to be aggregated in some way). Its introduction can be readily justified where groundwater resources are susceptible to irreversible degradation (**Boxes A & J**) and/or there is counterproductive competition amongst individual irrigation users (**Box E**) or between them and public water-supply. An alternative approach, applicable in some situations, is regulating or rationing the provision of electrical energy for rural groundwater pumping (which is showing much promise in the Gujarat Jyotigram Scheme in India) - this could be especially appropriate for weathered hard-rock aquifers (**Box E**), whose shallow groundwater production is characterized by rapidly escalating energy consumption with excessive drawdown, but parallel action would have to be taken to deter corrupt practices, protect poor farmers and constrain use of alternative energy sources.

- The regulatory instrument should have some of the following elements :
  - simple socially-accepted measures (eg. waterwell drilling bans, minimum waterwell spacing criteria)
  - individual groundwater abstraction/use rights (or licenses), either at a specified rate or allocation share, subject to periodic review and adjustment in the light of aquifer behavior – avoiding the

Table 2 : Summary of progress on groundwater resources management and the future outlook in the World Bank-supported pilot areas

AQUIFER SYSTEM Province/Country (date of last review)	GROUNDWATER RESOURCE MANAGEMENT progress achieved	future vulnerabilities
Carrizal Aquifer Mendoza-Argentina (2008)	• comprehensive waterwell inventory • practical use charging via energy consumption • effective waterwell drilling ban and constraint on spatial transfer/reactivation of use rights to mitigate groundwater salinization	• weak association of groundwater-only users • groundwater use rights still in perpetuity • strong economic pressure on public administration to relax drilling ban before adequate monitoring
Apodi Aquifer System Ceara & Rio Grande do Norte-Brazil (2009)	• RG do Norte implemented effective waterwell drilling ban in 2002 during intense drought • first national inter-state groundwater resource agreement for coordinated management action • supported by ANA through promotion of major joint evaluation and monitoring program to strengthen/harmonize scientific base	• interest amongst many stakeholders waning after high rainfall period • state government agency on one side has limited professional capacity and on other is rather inexperienced in practical resource administration • aquifer extremely vulnerable to pollution by agrochemicals
North China Plain Aquifer Guantao County-China (2009)	• widespread implementation of 'real water savings measures' in agricultural irrigation • comprehensive waterwell inventories and good monitoring of groundwater use/levels/quality • implemented real-time remote sensing of total evaporation providing strong technical basis for evaluating resource use/water productivity	• rationalization of abstraction licenses and mobilization of users in resource management lagging seriously behind promotion of irrigation water management • major socioeconomic pressure to expand industrial activity and meet corresponding groundwater resource demands
Souss-Chtouka Aquifer Agadir-Morocco (2009)	• consultative aquifer management plan prepared, including demand management and supply-side measures backed by both incentives and regulations	• insufficient personnel, financial resources and technical equipment for regulatory enforcement • lack of formal mechanism for full user representation in plan implementation and cumbersome legal procedures for enforcement
Weathered Hard-Rock Aquifer Micro-Watersheds Andhra Pradesh & Maharashtra States-India (2009)	• extensive and promising experience in AP State of promoting community-based action on localized micro-watersheds • Hivre Bazaar (MH) is outstanding example of village-level action leading to aquifer sustainability and much improved rural livelihoods – whose leader appointed as SG Ambassador to replicate success statewide	• although strongly supportive of village-level action, State groundwater agencies lack sufficient trained staff and clear remit to undertake 'lighthouse function' to replicate, sustain and evaluate community-based groundwater use management • lack of coordination of efforts between Union and various State government department initiatives, as well as those of national/international donors
Gangetic Alluvial Plain Aquifer Jaunpur Branch, Uttar Pradesh State -India (2008)	• introduction of a new over-arching state government apex agency for water resources • integrated water modeling (crop-soil-canal-aquifer) as basis for conjunctive management • elaboration of groundwater micro-management plans according to land zoning to promote more sustainable and efficient conjunctive use	• major investment required in canal rehabilitation, waterwell construction, rural electrification, land restoration, etc required • potential problem with enforcing existing 'operational codes' for canal-water distribution • essential that conjunctive use principle embraced fully by all users
Indus Peneplain Aquifer Central Punjab-India (2009)	• highly successful implementation of SG ordinance delaying paddy-rice transplantation with high level of compliance by farmers	• possible failure of SG to recognise critical role of many unlined irrigation canals in aquifer recharge • strong competition for available groundwater resources from numerous cities/towns
Silao-Romita Aquifer Guanajuato State – Mexico (2007)	• sound groundwater stabilization plan prepared and aquifer user management association (COTAS) established more than 10 years (with appropriate constitution and finance) • successful in raising general awareness through watershed protection program	• reluctance to confront harsh reality of limited renewable resources, and to define and finance exit solution from some agricultural practices • failure to devolve groundwater use rights admin from federal to state-level and COTAS
Lower Ica Valley & Pampa Villacuri Aquifers Ica – Peru (2010)	• ANA has put groundwater sustainability concerns high on national political agenda • reasonable long-term data available on groundwater resources and aquifer behavior	• inadequate staffing levels and limited budget allocations for local regulatory action • reluctance to confront harsh reality of limited renewable resources • risk of inadequate coordination between numerous government agencies and stakeholder groups

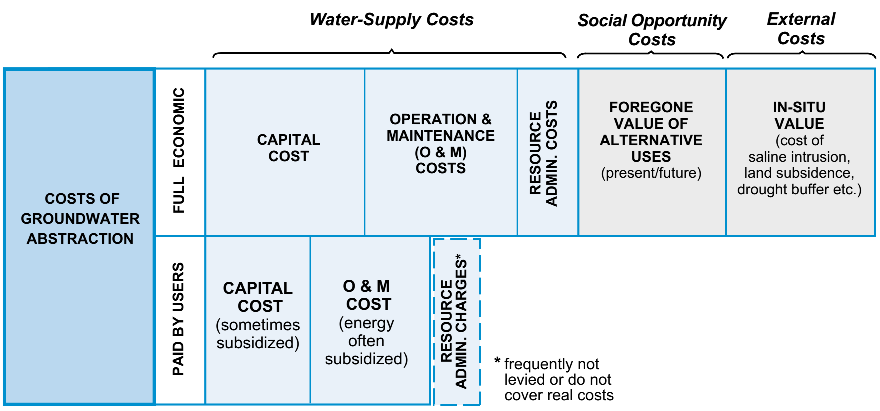
concept of 'rights in perpetuity'
- spatial constraints on transferability of waterwell rights (to specified zones of the groundwater body or aquifer system) and as regards type-of-use
- provision for sanctioning illegal waterwell drilling and illegal waterwell abstraction levels.

● The following related issues can be critical to success :
- up-to-date waterwell inventories (including both technical and social data) are needed for drawing -up user profiles to guide community participation and analyse use drivers
- groundwater use rights that are also coordinated with permits for surface water diversion and use
- political will to counteract any vested interests and corruption.

Moreover, use regulation alone may not be enough to manage groundwater resources successfully – and economic incentives for demand management measures can help in promoting compliance.

● Groundwater resources tend to be undervalued, especially where their exploitation is uncontrolled. In this situation the exploiter of the resource (in effect) receives all the benefits of groundwater use but (at most) pays only part of the costs (**Figure 6**) – and this undervaluation often leads to economically inefficient resource use.

Figure 6 : Comparison between true cost of groundwater use and that normally paid by users



● Charging groundwater resource abstraction fees is the most direct method to ensure that an incentive exists to economise on groundwater use. In this system users pay a 'resource abstraction (or commodity) fee' based on volumetric use (preferably metered rather than authorised) – although it is usually practical to exempt small self-supply domestic users. Unfortunately agricultural use is still rarely metered – and thus controlling irrigation use is not as straightforward as that of industry or commerce. Also, vested interests can conspire against charging large commercial farmers and social interests often justify exempting smaller, subsistence farmers (although they must be registered if their rights are to be safeguarded). Alternative techniques can be employed to estimate actual abstraction or use, including:
- estimation of the volume pumped from metered rural electricity use (**Box A**)
- estimation of the volume abstracted from pump rating or capacity and assumed operational schedules
- assessment of actual groundwater consumption by crop type and cultivated area, (although this is

often less than the potential evaporation) and it is preferable to use remote-sensing or detailed soil-water balances to map this at field-scale (**Box C**).

All of these indirect approaches need a sound inventory and base-map of waterwell locations, pump installation, electricity meters, area actually irrigated – and such information can be generated in part from the interpretation of satellite imagery and maintained in a GIS (**Figure 7**).

- Trading of groundwater use permits or allocations can facilitate the transfer of groundwater to higher-value uses in situations of 'capped total abstraction', in a manner acceptable to all parties, thereby promoting economic growth whilst diminishing social tension. The resultant establishment of a 'groundwater market' refers to the market trading of use rights or allocations (and not to the sale of bulk water-supply or the transfer of such rights at the time of property sale and land deed transfer). A gradual approach is essential – first putting into place adequate use measurement, establishing and defining use rights and water-user participation mechanisms. Once this is achieved all or part of a groundwater right or allocation could then be made temporarily or permanently tradable – this is not a substitute for resource regulation but a complement which requires additional effort in terms of public administration in return for additional economic benefits to society.

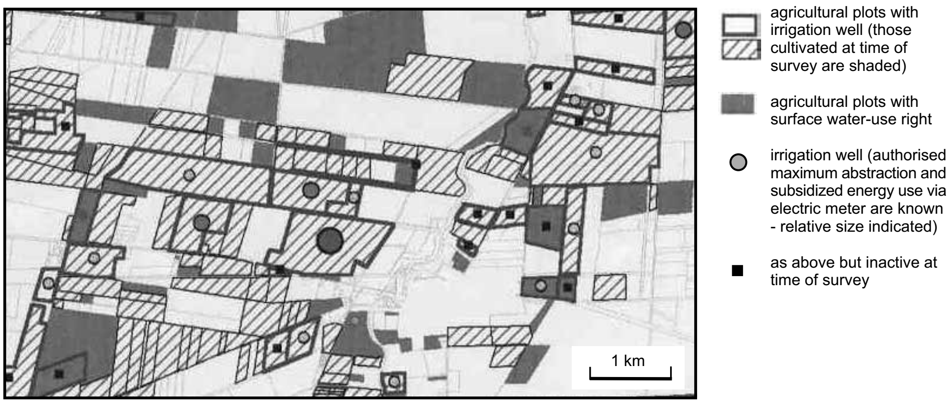
Community Participation and Self-Regulation

- Some degree of community stakeholder participation is essential for groundwater resources management, regardless of the status of regulatory and economic instruments. It can take many forms. At the most basic level it can occur without any action from a water-resource agency – examples existing of groundwater managed locally through community norms alone.

- Stakeholder participation in groundwater management can take place at various territorial levels ranging from village to aquifer system or even river-basin level (see **GW•MATE Briefing Note 6**) – and should be encouraged as an important contribution to groundwater conservation, management and protection. In the case of a major aquifer, there will often be many thousands of users, and enforcement of waterwell use controls (by whatever method) will only be possible with user involvement.

- It is desirable that active participation of users in groundwater resource management be promoted through aquifer management associations, through which users exert peer pressure for the

Figure 7 : Satellite imagery used to map land irrigated by groundwater (and surface water) with corresponding waterwells and electrical energy connections



achievement of management goals and collaborate through provision of data on waterwell use and levels. In this context it is important to distinguish between Irrigation Water User Associations (which are needed to improve and maintain effective irrigation-water services) and Aquifer Management Organizations (whose activities are directed to resource sustainability) (**Box H**). In situations where an aquifer underlies more than one province or country, special additional agreements will be needed and facilitation from central government may also be required (**Box E**).

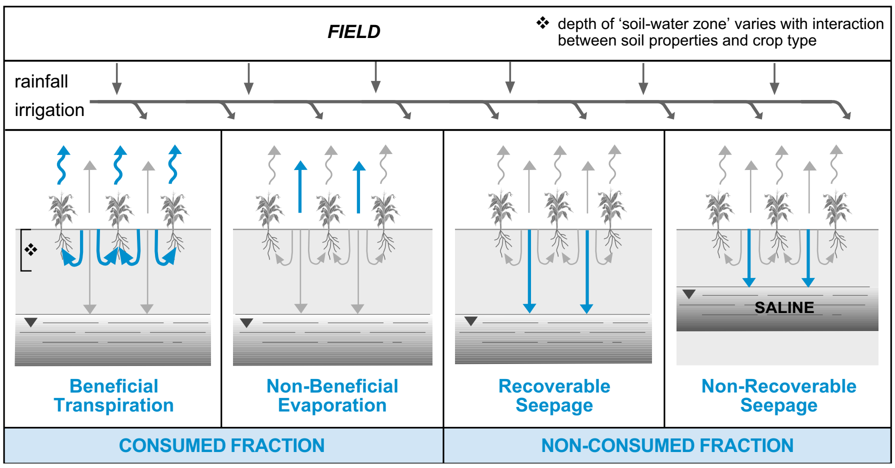
- Community self-regulation of groundwater resources is a step further, and may be achievable in certain hydrogeological conditions and socioeconomic circumstances (**Box E**) – but even then the local groundwater resource agency has a key role to play as a permanent 'lighthouse' in support of the sustainability of community action and its replication in similar areas under their jurisdiction.

Finance of Local Demand and Supply-Side Measures

- Mobilizing finance for improvements in 'irrigation water efficiency' can be a key element in any groundwater resources management action plan (**Box C**). But such improvements do not necessarily equate to real groundwater resource savings, and without parallel investments in demand management, the reverse is quite often found to be the case. This is because a substantial proportion of the so-called 'losses' of 'inefficient irrigation' (eg. gravity flood application to permeable soils) are in fact returns to groundwater. An extreme example of the effect of land management changes in irrigated agriculture on groundwater recharge rates (and thus on resource availability and quality) is abandonment of the traditional practice of spate irrigation in mountain-front areas, where fields are deliberately flooded in the wet season to induce infiltration and increase aquifer dry-season storage (**Box J**).

- When attempting to use improvements in irrigation technology for groundwater management (**Box C**), it is essential to combine this with :
  - a detailed understanding of the soil-water balance (**Figure 8**)
  - measures to reduce groundwater use rights in line with the increase in groundwater consumptive use
  - provisions to control (and probably reduce) total irrigated area.

Figure 8 : Fate of irrigation water applications to permeable soils and their relationship with groundwater



- It will also be necessary to mobilize finance for groundwater recharge enhancement, and its availability can provide an initial focus for community participation. However, while rainwater harvesting and recharge enhancement appropriate to local hydrogeologic conditions should be encouraged (**Box E & J**), they are not usually the solution to groundwater resource imbalance and pursuing them in isolation (as opposed to part of a balanced suite of management measures) may merely result in increased groundwater demand.

Alignment of Food and Energy Macro-Policies

- Since irrigated agriculture is by-far-and-away the predominant consumer of groundwater resources in many countries, macro-economic policies in the food and energy sectors can be very important drivers of groundwater use. Thus improving the alignment of related policies with sustainable groundwater management objectives greatly facilitates local management efforts. For instance, eliminating guarantee prices or subsidies for the cultivation of highly water-intensive crops (like paddy rice or sugarcane) in areas of scarce groundwater and surface-water will greatly aid resource management. Another example is exercising control on the date of planting-out paddy rice (**Box G**).

- The major cost in groundwater abstraction (once a waterwell is constructed) is the energy required to lift water. This cost will depend not only on water-table depth, aquifer characteristics and well efficiency, but also linearly on the unit cost of energy for pumping. Thus, energy (rural electricity or diesel fuel) pricing can be a useful tool to influence groundwater pumping trends in the absence of adequate water resources administration capacity or political will to undertake direct volumetric charging – although in cases where the cost of energy and groundwater is a small proportion of total agricultural production cost the scope may be more restricted than it first seems (**Box H**).

- Paradoxically, in many areas of the world, energy prices are used in the opposite way, with large subsidies on rural electricity supplies in place to decrease farming costs and in many cases to go some way to reducing the price differential between irrigation with groundwater and canal-water (which itself has a long history of being highly subsidized). Although rural energy subsidies can often be politically justified it has to be recognized that :
  - the adoption of a flat-rate rural electricity tariffs is perverse, since it results in farmers becoming insulated from one of the major cost items associated with falling water-table, and also the possibility of damaging the economics of the power utility must be assessed (**Box E & G**)
  - a critical consideration must always be the energy consumption (kWhr/ha) of crop production
  - while it is legitimate to subsidise poor farmers to improve livelihoods, better targeted subsidies to cover part of their estimated energy bill will be preferable since they then have an incentive to use water more efficiently.

  Similar considerations apply to the subsidy of fertiliser and pesticide, which can cause serious complications for groundwater quality if used inappropriately – and subsidies should be targeted to more environmentally-friendly agrochemicals.

- At the broader level of agricultural policy, some international trends could either substantially increase or decrease groundwater irrigation demand including :
  - national strategies to cultivate biofuels (such as sugarcane, soya beans, maize, etc), which could require (or benefit from) groundwater irrigation and, if their price was guaranteed extend the 'frontier' of groundwater irrigation use

- efforts to promote 'virtual water trade' by exporting high water-use crops (such as rice, maize, etc) from wetter to drier countries, amongst other things reducing demand for groundwater irrigation in the latter.

Corollary on Groundwater Conjunctive Use

- The spontaneous unplanned drilling of waterwells by farmers in and around major irrigation-canal commands has occurred very widely as a coping strategy in the face of inadequate irrigation-water service levels, especially in alluvial aquifer systems. In many cases, as a result, a substantial proportion of the total water-supply is provided from waterwells. It is very sound practice to use natural aquifer storage to buffer temporal and spatial variability in the availability of canal-water for irrigation, but for this not to encounter sustainability problems a sound understanding of surface water-groundwater relations (both natural and perturbed by irrigation practices), together with the character and distribution of any groundwater salinity hazards, is required – and this varies significantly down-the-length of major river basins as well as with climatic regime (**Figure 9**).

- If conjunctive use can be promoted on a more planned basis, it offers a major opportunity of increasing agricultural production (through improvements in overall cropping intensity and irrigation water productivity) without compromising groundwater use sustainability – and **Box F** provides a classic example of this situation. Planned conjunctive use of groundwater and surface water for irrigated agriculture is also a realistic 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.

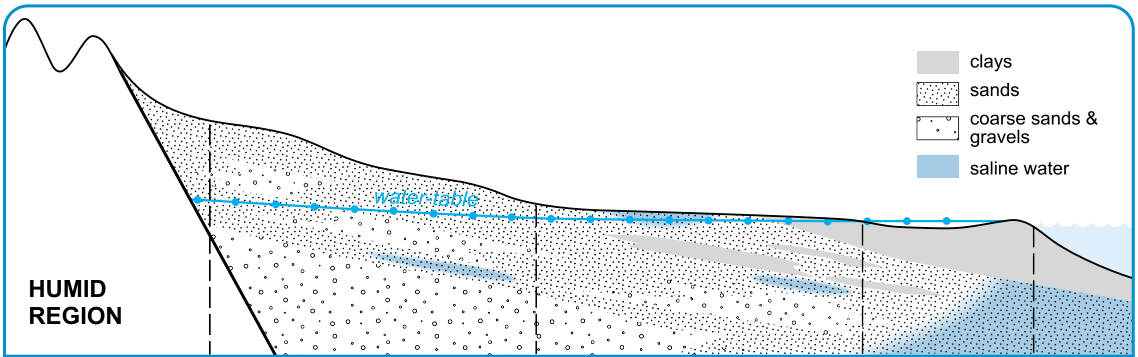
- The Pakistan Punjab provides a good example of evolution to planned conjunctive groundwater use. Initially some 10,000 waterwells were constructed by state government to tackle problems of land water-logging and salinization in major alluvial irrigation-canal commands by lowering the water-table. The success of this venture, and the fact that it concomitantly provided a reliable new irrigation water-supply led to a boom in private waterwell construction, such that the alluvial aquifer is now exhibiting stress in some areas (with increased pumping costs, groundwater salinization by up-coning and soil deterioration due to irrigation with brackish water). These problems are being addressed in a series of pilot projects seeking an improved balance between groundwater and surface-water use.

- 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.

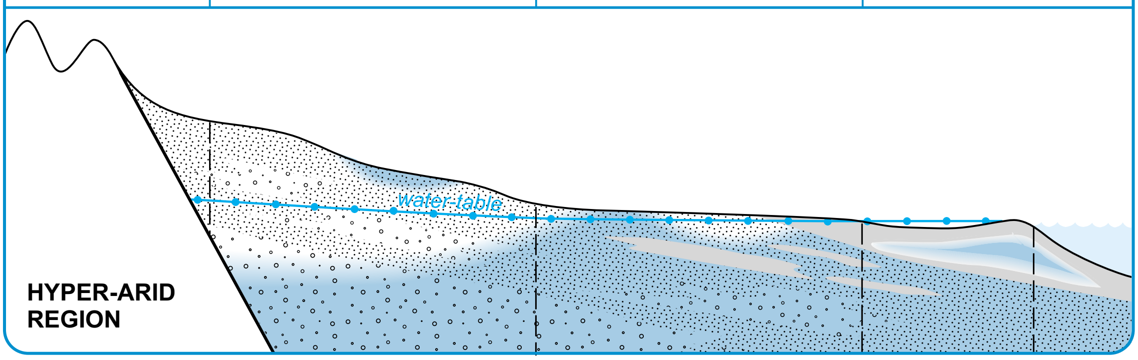
Implementing Management Action Plans

- For the public administration to achieve successful implementation of a groundwater resource management plan, a careful mix of stakeholder nurturing and administrative enforcement is required, supported by an effective information and communication system. This will be true whatever balance of instruments and measures is chosen on the basis of hydrogeological setting and socioeconomic condition (**Figure 5**).

Figure 9 : Summary of hydrogeological conditions in major alluvial aquifers and their climatic variation with water resource management implications



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/salinization; 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 mobilized 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



Feasibility and Enforcement

- It is prudent to undertake a feasibility analysis on the selected instruments and measures for groundwater resource management, which should include consideration of costs and benefits, and must also take into account local organizational capacity and the implied long-term recurrent costs. While it is relatively straightforward to estimate the costs of putting a given instrument or measure in place, it can be more difficult to estimate the value of the long-term benefits. An alternative option in this respect is a cost-effectiveness analysis – comparing different policy options to achieve the same management target.

- Perhaps the most crucial issue in making regulatory and charging instruments work in the cause of sustainable groundwater resources is achieving a reasonable level of compliance – given that ground-water use is a highly- decentralized activity involving many private users who have normally drilled their own waterwells, installed their own pumping equipment and are following their own pumping schedules. It will thus be necessary to impose sanctions for non-compliance – and this will require political support, organizational capacity and a sound strategy (based on penalizing very publically a few serious cases of non-compliance and resisting any related corruption).

Planning and Communication

- To implement groundwater management instruments and measures on-the-ground a clearly-phased and fully-budgeted plan must be agreed by all the main actors involved, and its implementation and impact continuously monitored. An example of the rationale and structure of such a plan is illustrated in **Box D**. And to implement most types of groundwater management plan a strong local government agency is required, but in some cases this will not be enough since without the full cooperation and sensitive facilitation by national government success may not be achieved (**Box H**). The 'push' of local groundwater management champions and the 'glue' of institutional coordination are important ingredients for successful implementation.

- To address the issue of sustainable groundwater use for irrigated agriculture, which has numerous inter-sectoral links and other complexities, an effective Information & Communication System is required. It should provide both fundamental technical information on groundwater resource status, trends and vulnerabilities, and on groundwater users, and also a guide to the complex network of public agencies and stakeholder organizations involved. The focus as regards stakeholders should be on building capacity to access, use and generate information – thus in groups with different capacities both traditional community outlets and modern information channels need to be considered.

SUMMATION AND FORWARD LOOK

- The greatly increased utilization of groundwater resources in many developing nations for irrigated agriculture over the past 15-25 years, and the emerging evidence of widespread excessive exploitation, does not yet represent a 'resource crisis' – mainly because the volumes of groundwater in natural aquifer storage are capable of 'buffering' over-exploitation for numerous years. But resource sustainability issues need to be confronted and addressed, and this is most pressing in numerous areas where it is accompanied by insidious mobilization and accumulation of groundwater salinity and/or where a significant component of groundwater resources abstracted are non-renewable.

- Given the widespread major dependency on groundwater for agricultural irrigation, and the very large private and public investments in irrigated agriculture, there is a pressing need for matching investments in strengthening groundwater resource governance and practical management (including use measurement, resource administration and monitoring, and user awareness and participation). In most developing nations, groundwater resource accounting in areas of irrigated agriculture remains very weak. This problem has a number of facets :
    - lack of momentum towards universal metering of larger groundwater abstractions and thus inevitable uncertainty over the level of resource use (given the limitations of indirect methods of estimation)
    - restricted dialogue and mutual understanding between agronomists and hydrologists on soil-water balances for irrigated cropping on permeable soils

- lack of appreciation of the frequent importance of unlined irrigation-canal networks for aquifer recharge, especially in semi-arid terrains.

This inevitably means that often the only data to guide groundwater management are water-table trends, with the handicap that these are usually tardy indicators and cannot be directly related to specific cropping and irrigation management practices.

- Recent increases in agricultural groundwater use in part reflect a rising demand for 'precision irrigation' with pressurized systems, which offers an adaptable platform for conversion to the intensive cultivation of higher-value crops – and increased incomes from smaller irrigated areas is an attractive option in the quest for groundwater resource sustainability. But whether this trend follows a 'sustainable path' will depend on the detail of irrigation-water management and whether 'real water-resource savings' are pursued and groundwater use rights or allocations are capped in consumptive use terms.

- There will, however, be inevitable market-related and risk-defined limits on the scope for conversion to high-value cropping, and the production of staple-crops (wheat, maize, rice, etc) will remain a very important (and probably the predominant) component of groundwater irrigation in most developing nations. In most cases there exists a major need to increase crop yields through improving soil management, seed-density and type, fertilizer and pesticide use to eliminate nutrient constraints or pest impacts on crop growth. But this will inevitably have impacts on both groundwater recharge and quality through increasing both consumptive groundwater use per unit area and nutrient and/or pesticide leaching. These impacts thus need to be soundly evaluated, with practical efforts being made to minimize them through controlled practices at field level.

- The 'socialization' of responsible long-term groundwater resource use through mobilization of users in management are critical pre-requisites for sustainable groundwater irrigation use. But community self-regulation is only likely to be sufficient alone in the case of subsistence use of highly-localized and low-storage groundwater systems – and in most cases stakeholder participation has to be incorporated within a balanced package of resource management approaches.

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