PERSPECTIVES PAPER

Global Water Partnership

Groundwater Resources and Irrigated Agriculture

– making a beneficial relation more sustainable

FAO/J.C. Henry

Globally, irrigated agriculture is the largest abstractor and predominant consumer of groundwater resources, with important groundwater-dependent agroeconomies having widely evolved. But in many arid and drought-prone areas, unconstrained use is causing serious aquifer depletion and environmental degradation, and cropping practices also exert a major influence on groundwater recharge and quality. The interactions between agricultural irrigation, surface water and groundwater resources are often very close – such that active cross-sector dialogue and integrated vision are also needed to promote sustainable land and water management. Clear policy guidance and focused local action are required to make better use of groundwater reserves for drought mitigation and climate-change adaptation. To be effective policies must be tailored to local hydrogeological settings and agroeconomic realities, and their implementation will require appropriate 'institutional arrangements' (with a clear focal point and statutory power for groundwater management), full involvement of the farming community and more alignment of agricultural development goals with groundwater availability.

A GWP Perspectives Paper is intended to galvanise discussion within the network and the larger water and development community. This Paper has been written by GWP Senior Advisor Stephen Foster and GWP Technical Committee Member Tushaar Shah. Feedback will contribute to future GWP Technical Committee publications on related issues.

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GWP is a global network of 13 Regional Water Partnerships, 80 Country Water Partnerships and more than 2,600 Partner organisations in 164 countries.

GWP was founded in 1996 by the World Bank, the United Nations Development Programme (UNDP), and the Swedish International Development Cooperation Agency (SIDA) to foster integrated water resource management (IWRM).

IWRM is the coordinated development and management of water, land and related resources in order to maximise economic and social welfare without compromising the sustainability of eco-systems and the environment.

The network is open to all organisations involved in water resources management: developed and developing country government institutions, agencies of the United Nations, bi- and multi-lateral development banks, professional associations, research institutions, non-governmental organisations, and the private sector.

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Towards Integrated Urban Water Management (2011)
Increasing Water Security - A Development Imperative (2012)
Water in the Green Economy (2012)
Groundwater Resources and Irrigated Agriculture – making a beneficial relation more sustainable (2012)

WHERE ARE WE NOW ?

Patterns and Drivers of Intensive Groundwater Use

The last 20-30 years have witnessed a 'global boom' in groundwater use for irrigation in areas subject to extended dry seasons and/or regular droughts (Llamas, 2005). In India, for example, the groundwater-irrigated area has increased 500% since 1960 (Shah, 2009). Satisfactory global statistics for groundwater irrigation are now available from a UN-FAO survey (Table 1). Today irrigated agriculture is the largest abstractor and consumer of groundwater, with almost 40% of all cultivated land under irrigation being 'waterwell equipped' – with large groundwater-dependent agroeconomies in South & East Asia. The nations with the largest groundwater-use areas are India (39 M ha) and China (19 M ha).

There are also many important examples of groundwater-based commercial-scale irrigation in Latin America, the Middle East & North Africa, which have become a vital source of local employment, national production and export income for the countries concerned, such as Brasil, Argentina, Peru, Mexico, Morocco & Egypt. These follow-on earlier examples of large-scale commercial irrigated agriculture using groundwater resources in parts of the USA, Israel & Spain.

A large proportion of the investment in irrigation waterwells has been by individual private farmers on an unplanned and uncontrolled basis. The groundwater boom in much of Asia is driven by demand-side, as well as supply-side, factors (Shah, 1993). Growing rural-population pressure has made intensive land-use imperative for small-holder livelihoods, and waterwells have helped small farmers to obtain a second (and even third) crop per year, and made irrigation possible beyond the canal command of government irrigation projects. Waterwells have also done more than surface-water irrigation systems to help such farmers diversify to higher-value crops. Additionally various other supply-side factors have further stimulated development:

- grants or low-cost loan finance for waterwell construction and irrigation hardware
- support for the collection and dissemination of hydrogeological knowledge on groundwater occurrence and potential
- certain developments in the technical evolution of waterwell pumps
- widespread rural electrification and in some cases provision of highly-subsidised electrical energy for pumping.

Table 1: Global survey of groundwater irrigation (derived from Siebert et al, 2010)

REGION	GROUNDWATER IRRIGATION Mha	propn total	GROUNDWATER VOLUME USED km3/a	propn total
GLOBAL TOTAL	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%

Benefits of Groundwater Use for Agricultural Irrigation

Groundwater is a 'very popular commodity' with farmers (Shah et al, 2007) since it:

- is usually found close to the point-of-use (often only a well's depth away)
- can be developed quickly at low capital cost by individual private investment
- is available directly on-demand for crop needs

EVOLUTION AND CONSTRAINTS OF WATERWELL PUMPS

The historical evolution of waterwell pumps and their power sources stretches back over many centuries, but certain developments were very significant when it comes to understanding the drivers of present-day groundwater irrigation:

- introduction in USA (California & Nebraska) from 1940s of electric or diesel-engined, shaft-driven, multistage, centrifugal pumps, capable of producing large yields for commercial-scale irrigated agriculture
- improvements of electric-submersible pumps in USA during 1950s to allow yields adequate for large centre-pivot irrigation
- major reduction in the capital cost of handpumps and small electric-engined pumps in India during 1980s, as part of UN Water-Supply & Sanitation Decade efforts, which were then adapted for low-cost shallow irrigation waterwells.

The former two facilitated groundwater use for large-scale commercial irrigation worldwide, and the third enabled the groundwater boom throughout South Asia since it allowed very small-scale farmers to install waterwell irrigation, following the failure of many government programmes for equitable access to groundwater using heavy-duty pumps and buried pipeline networks from the 1960s, due to a combination of techno-managerial factors.

(given a reliable energy source for pumping) and thus affords small-holders a high level of control year-round

- is well-suited to pressurised irrigation and high-productivity precision agriculture
- has 'democratised' irrigation by permitting irrigated agriculture outside canal command areas.

In developing and transforming nations the 'groundwater-irrigation boom' occurred at various economic levels (Garduno & Foster, 2010) – from subsistence farming to large-scale staple-crop production and commercial cash-crop cultivation. It has brought major socioeconomic benefits to rural communities and in many countries has helped to alleviate agrarian poverty through increasing food security – by ensuring water availability at critical times for crop growth and mitigating devastating

effects of drought on crop yields (Shah, 2009). In South Asia the groundwater boom has also largely been pro-poor, with marginal farmers of holdings smaller than 2 ha increasing their groundwater-irrigated area by three times more proportionally than farmers with more than 10 ha of land. And an 8-country study of limited small-holder irrigation in Sub-Saharan Africa, revealed that small farmers are attracted to groundwater irrigation because it facilitates the cultivation of vegetable cash crops for urban markets.

Concerns about Resource Sustainability

In most regions that experience 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. Moreover, groundwater (a common-pool, open-access resource) is also prone to the 'tragedy of the commons', with individual short-term interests prevailing over longer-term communal concerns – and its effective management requires collective action (Ostrom, 1990; Burke & Moench, 2000; Foster et al, 2009).

This situation has led to widespread depletion of groundwater resources, with the following collateral effects, which vary considerably in occurrence and intensity with hydrogeological setting:

- counterproductive competition between irrigation users

- conflicts with rural and/or urban drinking-water provision, making it more difficult to achieve MDGs
- impacts on natural aquifer discharge (spring-flow, riverbed flows), which result cumulatively in an unacceptable impact on 'downstream' surface water-flows
- degradation of important groundwater-dependent aquatic ecosystems.

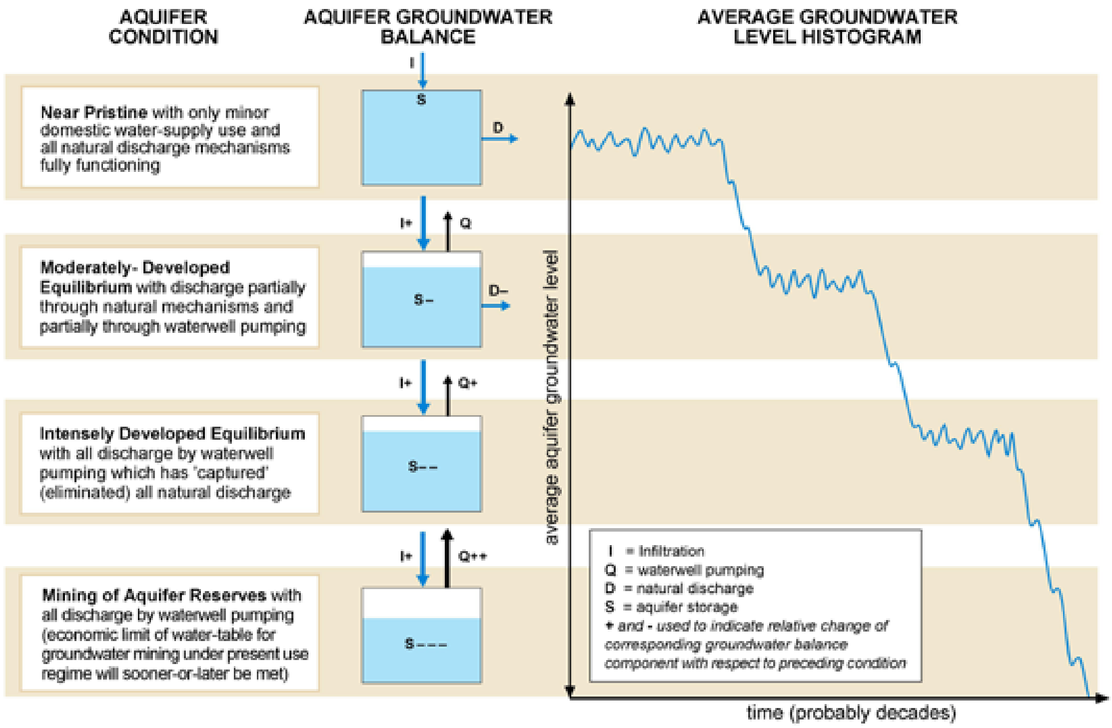
Conceptual misunderstandings about groundwater resources tend to occur rather widely and there is need to substitute myth with reality (Garduno & Foster, 2010) by:

- making a clear distinction between 'groundwater-only irrigation areas' and 'conjunctive-use irrigation areas', since these present very different prospects, approaches and challenges for resource optimisation
- focusing resource-management efforts on constraining consumptive use (rather than just groundwater withdrawals), especially in groundwater-only irrigation areas
- assessing groundwater-surface water connectivity in alluvial environments, as a basis for taking advantage of the opportunities of 'conjunctive management' whilst avoiding the risk of 'double-resource accounting'.

THE CONCEPT OF 'RESOURCE OVEREXPLOITATION'

Some discussion of this concept is necessary here, without getting hung-up over semantics. Clearly all groundwater abstraction has an 'impact' – since it diverts flow from elsewhere in an aquifer system and reduces natural discharge. The real question is when do such impacts become cumulatively significant (Figure 1). It may appear appealing to use an economic definition (ie: the costs of third-party effects, longer-term environmental impacts and lost resource opportunity exceeding short-term use benefits) – but in practice it is often difficult to assess the associated costs. Moreover, this does not consider the 'efficiency versus equity issue' – given that less-depleted groundwater systems favour more equitable access for the poor and often better protect ecological interests. But maintaining groundwater stocks against all depletion is rarely appropriate, especially in arid regions where (given the long periodicity of major recharge episodes) groundwater is critical for mitigating the impacts of surface-water drought and for providing time to allow transition to lower water-use economies to evolve.

Figure 1: The stages of groundwater resource development and their impacts



More generally, improvements in hydrogeological accounting are required to describe the detailed relationship between groundwater and irrigation, and the factors on which different recharge components depend (Foster & Perry, 2010).

Hazards of Excessive Groundwater Exploitation

Continuous groundwater depletion resulting from long-term excessive resource exploitation can in some cases result in a number of other serious consequences:

- the salinisation of aquifers – which is a very insidious and often complex process arising from a variety of physical mechanisms
- troublesome land subsidence due to the settlement of interbedded aquitards in alluvial and/or lacustrine formations

increasing (and in some cases spiralling) electrical-energy costs for pumping, especially where use is 'buffered' by subsidies or flat-rate tariffs – with serious implications for many electricity utilities and for the unit energy consumption and carbon footprint of irrigated agricultural production (Shah & Verma, 2008; Garduno & Foster, 2010).

The major cost component of groundwater production (once waterwells are constructed) is the energy required to lift water, which will depend on unit energy price, water-table depth, aquifer characteristics and well efficiency (which in some hydrogeological settings can decrease dramatically with declining water-table). Rural electricity pricing could thus be a very useful tool to constrain groundwater abstraction, but paradoxically it is often used in the opposite way with major subsidies in place to decrease farming costs and reduce water-price differentials.

Confronting the Harsh Reality of Weakly-Recharged Aquifers

In areas where current average annual rainfall is less than 500 mm/a or so, the associated rate of diffuse groundwater recharge to shallow aquifers is sensitive to soil-type and vegetation-cover, and can fall-off markedly to very low levels (Figure 2) – and more widely deeper aquifers may only be weakly-recharged due to their physical isolation by geological structure from the land surface.

THE DIAGNOSIS OF GROUNDWATER SALINISATION

In major areas of agricultural irrgation the salinisation threat to groundwater varies widely with overall hydrogeological setting and climatic regime, and even down-the-length of major river basins. It arises through a number of distinct and independent mechanisms:

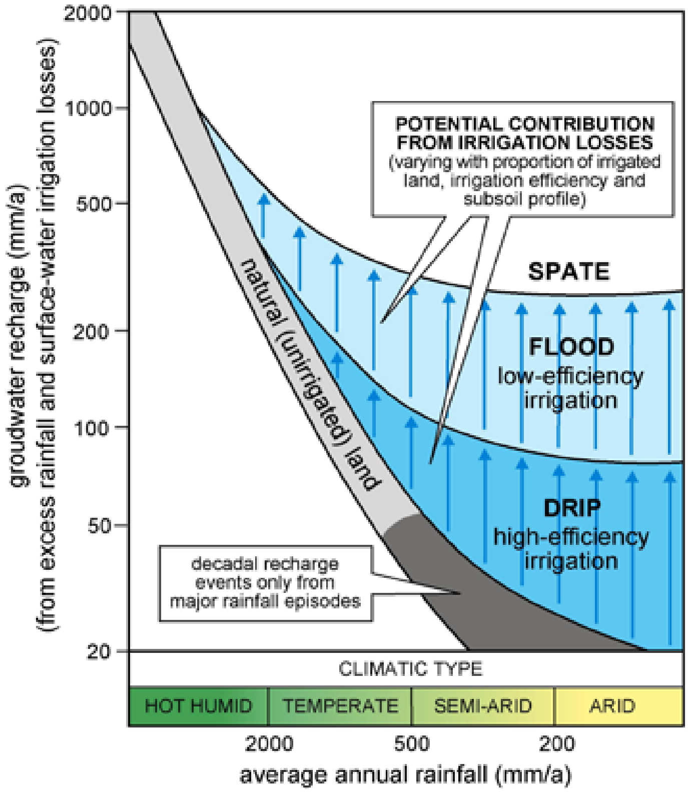
- rising water-table due to excessive canal seepage and/or field application in head-water areas leading to soil water-logging and phreatic salinisation, or sometimes naturally saline shallow groundwater becoming mobilised
- leaching of soil salinity across irrigation areas on first habilitation of arid soils and/or salt fractionation by 'efficient' irrigation, with accumulation in tail-end sections of canal commands if no groundwater outflow occurs
- more classical coastal lateral intrusion or inland up-coning of saline groundwater due to excessive abstraction of fresh groundwater
- additionally there are hyper-arid areas in which virtually all groundwater is naturally saline, except where some infiltration from surface watercourses and irrigation canals forms 'freshwater lenses'.

The implication is that groundwater salinisation threats need sound diagnosis, close monitoring and careful management.

Maintaining groundwater stocks against all depletion is rarely appropriate, especially in more arid regions where (given the long periodicity of major recharge 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. But in such conditions it is equally important to confront the implications of weakly-recharged groundwater systems, with both public administrations and private groundwater users coming to terms with this reality (Foster & Loucks, 2006) by:

- making every effort to ensure high efficiency and productivity of resource use
- undertaking careful use metering, with continuous monitoring and periodic evaluation of aquifer response
- considering the issue of intergenerational equity by investment in implementable 'exit-stategies', such as surface-water transfer and/or low water-use activities.

Figure 2: General relationship between ground-water recharge and annual rainfall indicating the potential contribution for surface-water irrigation returns



- *vertical arrows indicate the potential increase in groundwater recharge in scenarios of varying water-use efficiency, assuming that irrigaion losses freely infiltrate to an unconfined aquifer*
- *where local groundwater (not surface-water) is a major source of irrigation recharge and will NOT increase but 'recirculation' from irrigation returns will reduce net groundwater abstraction*

Groundwater Quality Impacts of Irrigated Agriculture

Agricultural land-use practices in general also exert a major influence on groundwater recharge quality (Foster et al, 2000; Foster & Candela, 2008) through:

- leaching of soil nutrients: this problem has been exceptionally widespread in the industrialised nations with (largely successful) attempts to increase grain, oil-seed, vegetable, fruit and milk production per unit area through the replacement of traditional crop rotations with near moncultures, but as yet has been less severe in the developing world where inorganic fertiliser applications have generally been much lower – in theory at least the problem of soil nutrient leaching should also be more manage-able in irrigated than rain-fed agriculture
- contamination with pesticides: a potentially serious problem but one more confined geographically to recharge areas of aquifers exhibiting high vulnerability to pollution from the land-surface, where the more 'mobile' pesticides (mainly certain herbicides and soil insecticides) have been regularly used at high application rates
- mobilisation of salinity: this issue is of very serious concern in arid and hyper-arid areas where the 'irrigation frontier' has (or is) being extended thorough clearing of native desert scrubland with high salinity levels retained in the subsoil profile.

HOW CAN WE IMPROVE SUSTAINABILITY?

In 'Groundwater-Only' Irrigation Areas

Pragmatic Approach to Management Interventions

A fundamental paradigm emerging from recent experience is that the hydrogeologic and socio-economic setting of individual aquifers supporting groundwater-irrigated agricultural development usually both define the groundwater management problem itself and constrain the most likely solution. A 'one-size-fits-all' approach to groundwater resource management is simply inadequate (Garduno & Foster, 2010), and it is necessary to tailor a package of management measures to the local hydrogeologic and socioeconomic setting. Moreover, groundwater resources also require an 'adaptive management approach', in which provisional decisions are made and measures taken based on best-available scientific evidence with subsequent monitoring of aquifer responses and social outcomes, and periodic adjustment of the management approach as necessary.

When it comes to the implementation of groundwater management action plans, careful attention will be needed to achieving appropriately balanced and vertically integrated 'institutional arrangements' (Figure 4) between:

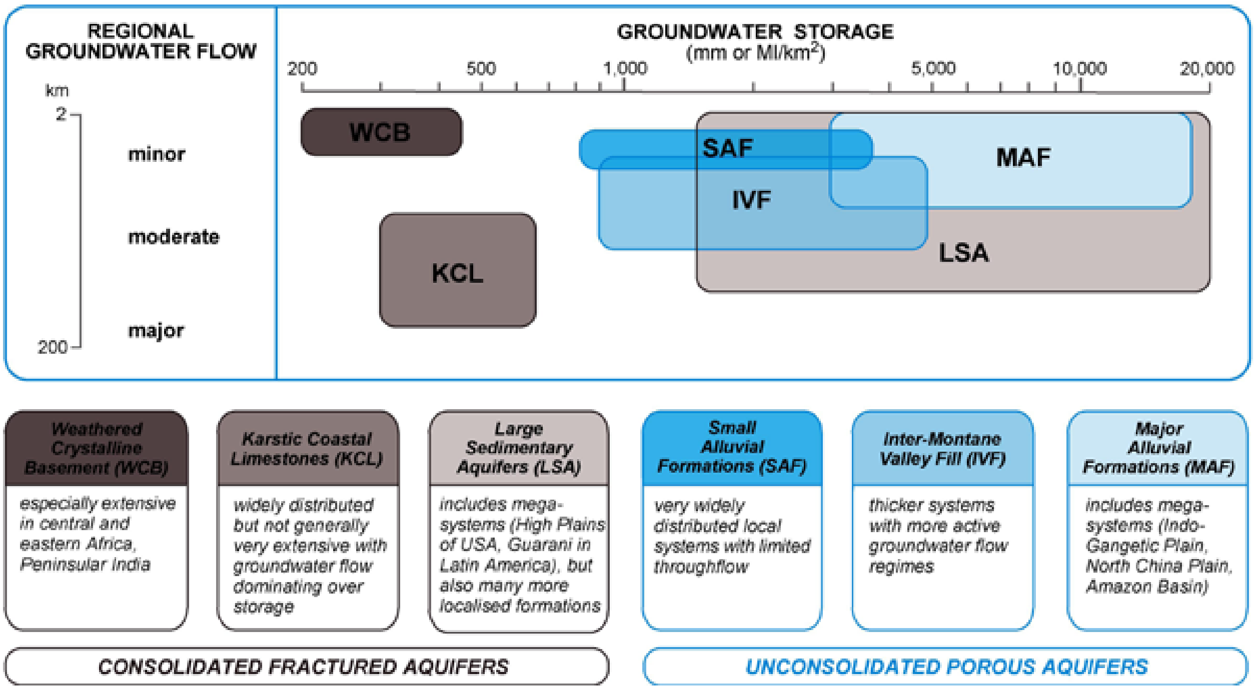
- community awareness raising, participation and self-regulation
- resource administration through use regulation and charging
- macro-policy interventions to constrain groundwater demand.

Moreover, the 'push' of a strong locally-based agency is required, together with the 'pull' of national government through sensitive facilitation, and a clearly-phased and fully-budgeted plan must

THE WIDE NATURAL VARIABILITY OF AQUIFER SYSTEMS

Aquifers have two fundamental characterisitcs – a capacity for groundwater storage and a capacity for groundwater flow. But the different geological formations that behave as aquifers vary very widely in the degree to which they exhibit these properties (Figure 3) – with volumes in drainable storage varying from very modest amounts (<500 Ml/km2) to vast volumes (>10,000 Ml/km2). Moreover, their areal extent varies widely with geological structure (from <10 km2 to >10,000 km2) and the scale of groundwater flow regimes similarly. Such 'hydrogeological diversity' has far reaching implications when it comes to considering realistic approaches to resource management.

Figure 3: Variation of typical groundwater storage and flow regimes with aquifer type



be agreed and owned by all the main actors involved. The effectiveness of plan implementation should be monitored in the long-term, and refined as appropriate.

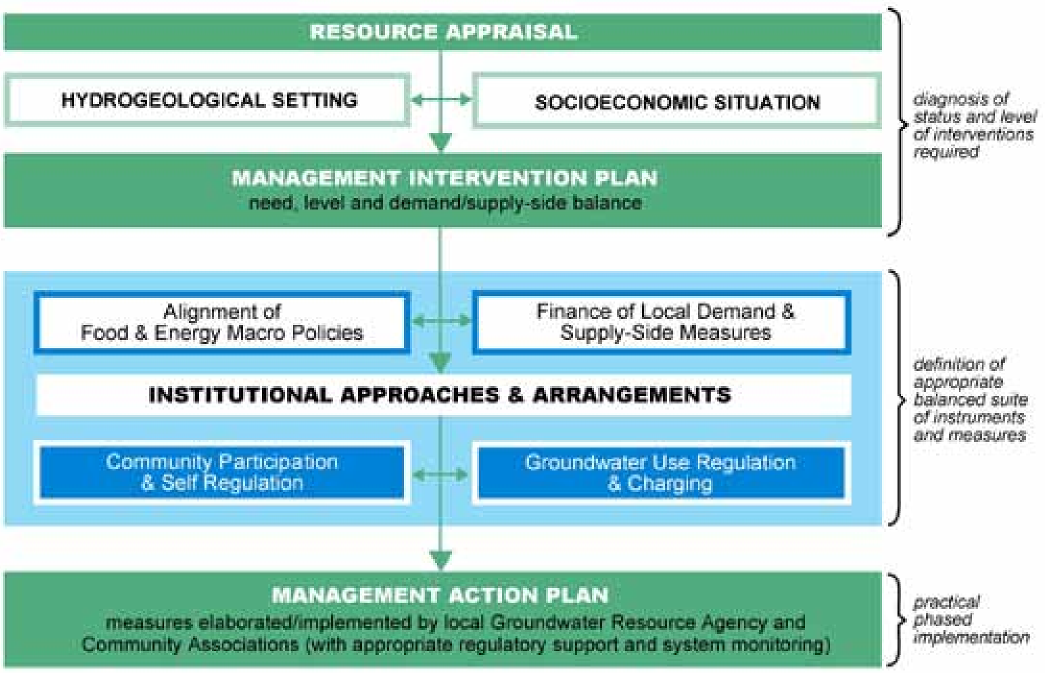
Identifying Appropriate Management Measures

Improvements in 'irrigation water-use efficiency' can be the key to increasing water productivity and reducing unit energy consumption in agriculture. They can also be a useful component of ground-water management action plans, but do not necessarily equate to 'real water resource savings' (Foster & Perry, 2010), because a substantial proportion of the so-called 'losses' associated with 'inefficient groundwater irrigation' often infiltrate and return to the aquifer. Moreover, progressive changes from gravity (flood) irrigation to pressurised (drip) irrigation inevitably result in a substantial increase in groundwater consumptive use, even if actual abstraction is successfully capped.

Where a concerted effort has been put into reducing losses via non-beneficial evaporation significant real water-resource savings have resulted, for example up to 30 mm/a in Guantao County-China (Garduno & Foster, 2010) for winter wheat/summer maize rotations receiving total irrigation of 400-460 mm/a.

An extreme example of the effect of land management changes in irrigated agriculture on groundwater recharge rates (and thus on resource availability and quality) occurs with abandonment of the traditional practice of spate irrigation in mountain-front areas, where fields are deliberately

Figure 4: Pragmatic framework for identification of a balanced approach to groundwater resource management in excessively-exploited aquifers



flooded in the wet season to induce infiltration and increase aquifer dry-season storage. This has occurred extensively, for example, in the Ica Valley of Peru with the introduction of intensive asparagus cultivation (Garduno & Foster, 2010). While there can be overriding reasons for this (such practice not being readily compatible with modern pressurised irrigation), if such a decision is taken alternative methods of ensuring groundwater recharge from flood run-off will need to be introduced.

When attempting to use improvements in irrigation technology for groundwater management, it is essential to combine this (Foster & Perry, 2010) with:

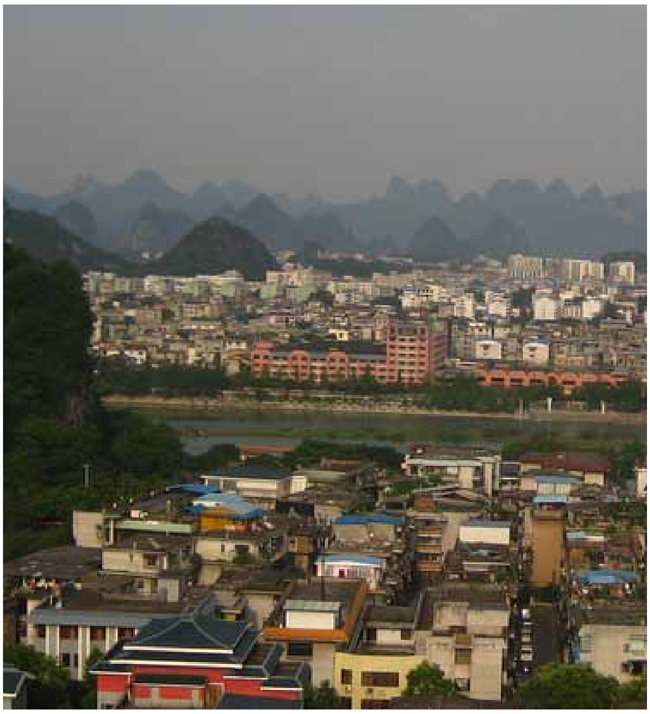
- a detailed understanding of the soil-water balance
- measures to reduce groundwater use rights in line with consumptive use
- provisions to control (and probably reduce) total irrigated area.

It will also be necessary to mobilise finance for groundwater recharge enhancement, since this can provide an initial focus for community participation. Under favourable hydrogeological conditions, as was the case at Hivre Bazaar (Maharashtra)-India (Garduno & Foster, 2010) and in larger areas of Saurashtra-Gujarat (Shah, 2009), such measures can provide a significant increment in local resource availability and be the key to mobilising the local irrigation community on a concerted effort of parallel demand management. However, while rainwater harvesting and recharge enhancement appropriate to local conditions should be encouraged, they are not usually the solution to groundwater resource imbalance and their pursual in isolation may merely result in increased groundwater demand. Moreover, volumetrically the effect of 'groundwater-friendly' agricultural land-use practices is generally more significant (because much larger land areas are involved).

The most direct approach to reducing groundwater irrigation demand (and consumptive use) is to constrain abstraction and effect a reduction in irrigated area. However, without concomitant action to sustain farmer incomes, by increasing water-use productivity through better husbandry to improve crop yields or cultivation of higher-value crops, such a policy can prove very difficult to implement and sustain.

Community Participation and Self-Regulation

A degree of community stakeholder participation is essential for groundwater resources management, given the frequently very large number of individual groundwater users involed (Burke & Moench, 2000; Shah, 2009), regardless of whether regulatory and economic instruments are also deployed. It can take many forms and can take place at various territorial levels ranging from village to aquifer system or even river-basin level – and should be comprehensively nurtured as an important contribution to groundwater conservation, management and protection, otherwise its effectiveness may become much reduced. This has found to be the case in many of the pioneering COTAS of Guanajuato-Mexico (Garduno & Foster, 2010).



It is desirable that active participation of users in groundwater resource management be promoted, in which users exert peer pressure for the achievement of management goals and collaborate through provision of data on waterwell use and levels (Garduno & Foster, 2010). This can be achieved:

- through aquifer management associations (as in Mexico above)
- some form of pact between local users and resource regulators (for example as in the Sousse River Basin Agency of Morocco).

Community self-regulation of groundwater resources (as has been successfully initiated in parts of India, for example at Hivre Bazaar (Maharashtra) and a considerable number of micro-watersheds in Andhra Pradesh State (Shah, 2009; Garduno & Foster, 2010)) is a step further, and may be achievable in certain hydrogeological conditions and socioeconomic circumstances – namely small localised groundwater bodies exploited by a socially-homogeneous group of users. But even here local groundwater resource agencies have a role to play as a permanent 'lighthouse' in support of the sustainability of community action and its replication in similar areas under their jurisdiction. In the absence of such permanent external support, community resource management tends to weaken and in time wither away. as the Andhra Pradesh experience shows some two years after donor project support was discontinued.

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. Its introduction can be readily justified where groundwater resources are susceptible to irreversible degradation and/or there is counterproductive competition amongst individual irrigation users or between them and the public water-supply.

The regulatory instrument should have some of the following elements:

- individual waterwell use rights or licenses, either at a specified rate or allocation share, subject to periodic review and adjustment in the light of aquifer behaviour (avoiding the concept of 'rights in perpetuity')
- groundwater use rights or licenses that are coordinated with permits for any surface water-use, and avoid 'double resorce accounting'
- aggregation of licenses for smaller users where suitable community associations exist, to facilitate water resources administration
- 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 waterwell abstraction.

Groundwater resources tend to be undervalued, especially where their exploitation is uncontrolled – when the resource exploiter (in effect) receives the benefits of groundwater use but (at most) pays only part of the costs – and this undervaluation often leads to economically inefficient resource use (Figure 5).

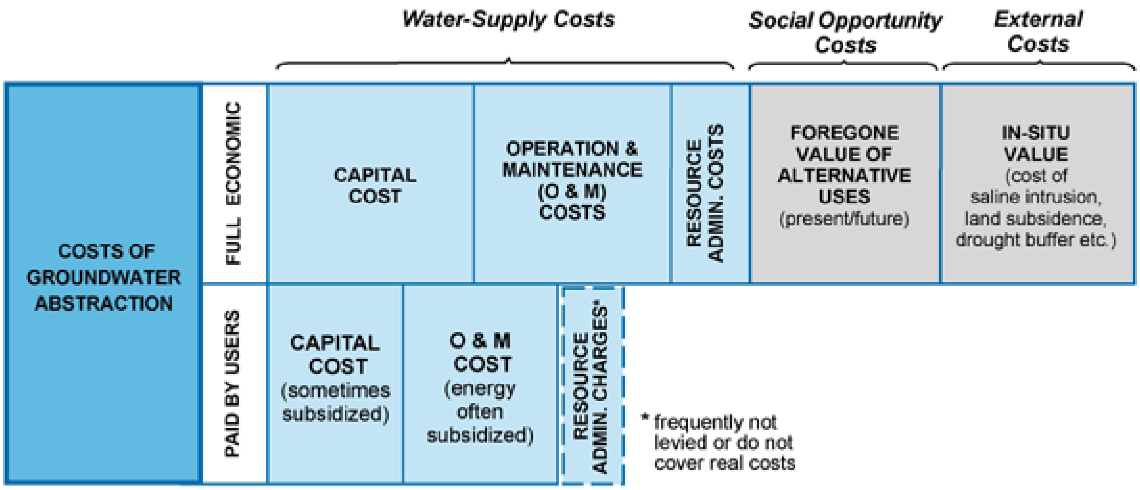
Charging groundwater resource abstraction fees is the most direct method to ensure that an incentive exists to economise on use. In this users pay a 'resource abstraction (or commodity) fee' based on volumetric use (preferably metered rather than authorised) – although it is usually practical to exempt 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. Alternative techniques are being employed to estimate actual abstraction or use, including:
- estimation of volume pumped from metered rural electricity use
- estimation of volume abstracted from pump capacity and assumed schedule

- assessment of actual consumption by crop type and cultivated area.

Groundwater regulatory approaches need a sound inventory of waterwell locations, pump installations, electricity meters and areas irrigated. Such information can be partly generated from satellite imagery and managed in a GIS – and an increasing number of examples of good practice in this regard (as an essential component of a solidly-based system of groundwater resource administration) can be found worldwide – for example in Mendoza-Argentina and the Apodi Plateau-Brasil (Garduno & Foster, 2010).

Figure 5: Economic-cost components of groundwater and those normally paid by users



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THE ROLE AND SCOPE OF 'GROUNDWATER MARKETS'

Trading of 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. 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). In recent years they have been successfully promoted in Victoria & New South Wales-Australia, but a much earlier initiative in the valleys of Central and Northern Chile encountered significant practical problems. 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 license or allocation can then be made temporarily or permanently tradable – not as a substitute for resource regulation but as a complement offering additional socioeconomic benefits.

It is sometimes argued that a 'regulatory approach' to groundwater resource management in water-scarce regions is often open to corruption, when resources become scarce and are capped. An effective 'public information and communication system' should thus be brought simultaneously into being so as to counter-balance any such tendendency.

Alignment of Food and Energy Macro-Policies

Since irrigated agriculture is by-far-and-away the predominant consumer of groundwater resources in many countries, improving the alignment of related food and energy policies with sustainable groundwater management objectives 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 water-scarce areas will greatly aid resource management. Other important policy interventions that can, in some cases, be considered at national or provincial government level include:

- exercising control over the date of planting-out paddy rice to reduce non-beneficial evaporation (a promising example of this is the statutory deferral of rice transplanting by 35-40 days in the Indian Punjab since 2008, which appears to be capable of making a real water-resource saving of 90 mm/a without negative impact on crop yields (Garduno & Foster, 2010))
- eliminating groundwater irrigation of animal feed (typically alfalfa and/or maize) in arid regions using scarce groundwater resources.

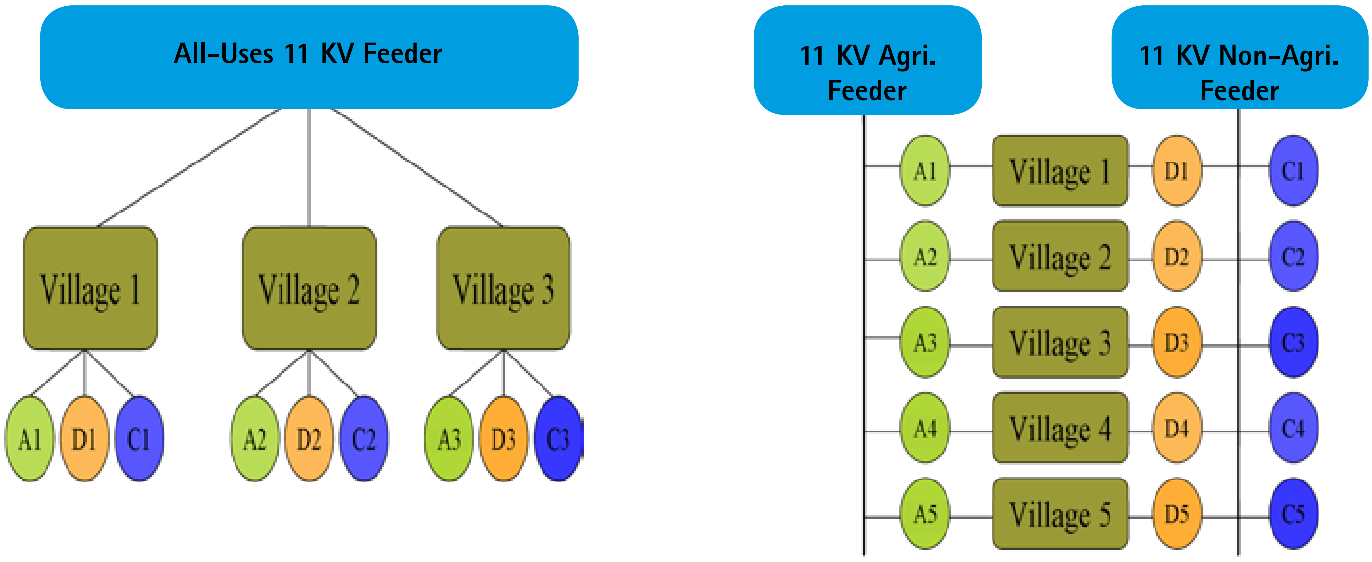
Although rural electrical-energy subsidies can sometimes be politically justified it has to be recognised that:

- flat-rate rural electricity tariffs are perverse, since they result in farmers becoming insulated from groundwater resource status and waterwell inefficiencies, and thus from the unit energy consumption (kWh/ha) of crop production
- while it is legitimate to support poor farmers to improve their livelihoods, better targeted subsidies to cover part of their estimated energy bill are preferable since they incorporate an incentive to use water more efficiently.

In India groundwater resource unsustainability is in considerable part the consequence of perverse electricity subsidies for waterwell irrigation. From the 1970's many state governments (desiring to achieve food and livelihood security) began offering subsidies, with some providing free electrical energy apart from a 'fixed connection charge'. In areas with rural electrification this widely resulted in rapidly declining groundwater tables, with no incentive to reduce use even where the real cost of pumping soared. The progressive elimination of such subsidies is required to make groundwater-irrigation sustainable, and to avoid technical and financial breakdowns of electricity utilities, but has now become a major political challenge.

A solution has been successfully piloted in Gujarat (Shah & Verma, 2008) – this involved 'rewiring' the rural electricity-distribution system, separating waterwell power from all other users (Figure 6), and then in effect 'rationing' the supply to waterwell irrigators. It has had three positive outcomes: capping aggregate groundwater draft, controlling electricity-utility losses and improving village electricity supplies. Moreover, it has given

Figure 6: Transformation of the rural electricity-supply network in Gujurat-India (the JGY Scheme) to allow control of the use of waterwells for agricultural irrigation



Before JGY **After JGY**

groundwater managers the option to constrain the groundwater-irrigation economy in line with resource availability (Shah et al, 2012). This approach could be especially appropriate for all areas of weathered hard-rock aquifer, whose shallow groundwater production is characterised by rapidly-escalating energy consumption with excessive drawdown – but parallel action has to be taken to deter corrupt practices, protect poor farmers and constrain use of alternative power sources.

Conjunctive Use in Major Alluvial Canal Commands

Spontaneous Conjunctive Use by Farmers

The spontaneous unplanned drilling of waterwells by farmers in and around major irrigation-canal commands on alluvial aquifer systems (Shah, 2009; Foster & Steenbergen, 2011) has occurred very widely as a coping strategy in the face of inadequate irrigation-water service levels consequent upon:

- poor canal maintenance and inability to sustain design flows
- poorly administered canal-water, allowing unauthorised or excessive off-takes
- insufficient surface water availability for dry season diversion
- rigid canal-water delivery schedules, unresponsive to crop needs.

The rate of growth of this phenomenon is remarkable, especially across the Indo-Gangetic Plain (Table 2).

Table 2: Evolution of spontaneous groundwater conjunctive use on the Gangetic Plain of Uttar Pradesh State-India

YEAR	PRIVATE IRRIGATION TUBEWELLS (no.)	IRRIGATED AREA	
		TOTAL (Mha)	PROPN BY TUBE-WELLS
1950-51	------	3.04	16%
1960-61	5,040	4,16	34%
1980-81	465,970	8.80	29%
2000-01	573,050	11.87	33%

In effect, conjunctive use of groundwater and surface water, in some form or other and with varying degrees of effectiveness, is capable of achieving:

- much greater water-supply security, taking advantage of natural aquifer storage
- larger net water-supply yield than generally possible using only one source alone
- better timing of irrigation-water delivery, groundwater being rapidly deployed to compensate for shortfalls in canal-water at critical times in the crop-growth cycle
- reduced environmental impact, through counteracting land water-logging and salinisation.

It is noteworthy also that private groundwater use is often characterised by higher water productivity (kg crop or US$ profit per ha/m3), despite (or perhaps because of) the fact that the unit cost of this water-supply to the user is much higher (Foster & Steenbergen, 2011).

In many cases 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 uncontrolled it sometimes results locally in aquifer depletion to water-table levels that complicate the deployment of low-cost (ground-level) lift-pumps for irrigation. Spontaneous conjunctive use sometimes encounters increasing groundwater salinity, which if not adequately diagnosed and controlled will result in a serious subsequent decline in agricultural productivity and threat to drinking water-supply security.

Opportunities For Conjunctive Management

If conjunctive use can be promoted on a more controlled basis, it offers a major opportunity for increasing agricultural production (through improvements in overall cropping intensity and irrigation water productivity) without compromising groundwater use sustainability (Foster & Steen-bergen, 2011). Planned conjunctive use of groundwater and surface water for irrigated agriculture is also a realistic adaptation strategy to accelerated climate change.

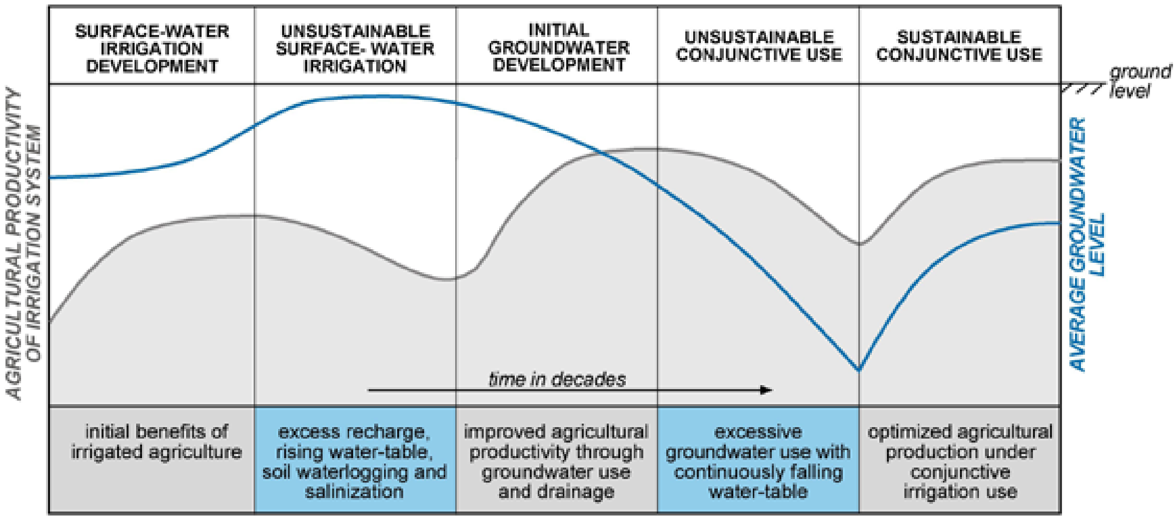
A good example of the benefits of conjuctive use and challenges of optimised conjunctive management comes from Uttar Pradesh-india, where the Jaunpur Branch Canal Command has been the subject of detailed evaluation (Garduno & Foster, 2010) – improved distribution of irrigation canal water and irrigation tubewell use (plus some reclamation of salinsed land) is capable sustainably of increasing the cropping intensity of the 'rabi wheat/karif rice' rotation from 1.4 to 2.2 if the considerable institutional, social and economic impediments can be overcome.

The key criterion is to find a balance of overall groundwater use which avoids long-term water-table decline whilst countering rising water-table and the menace of land water-logging and soil salinisation (Figure 7). A sound understanding of surface water-groundwater relations (both natural and perturbed by irrigation), together with the character and distribution of any groundwater salinity hazards, is a pre-requisite.

In this context, lining of primary and/or secondary irrigation-canals is a high priority :

- on arid alluvial plains where the phreatic aquifer

Figure 7: Evolution from spontaneous conjuctive use to conjuctive manangement of groundwater and surface-water resources in major alluvial aquifer systems

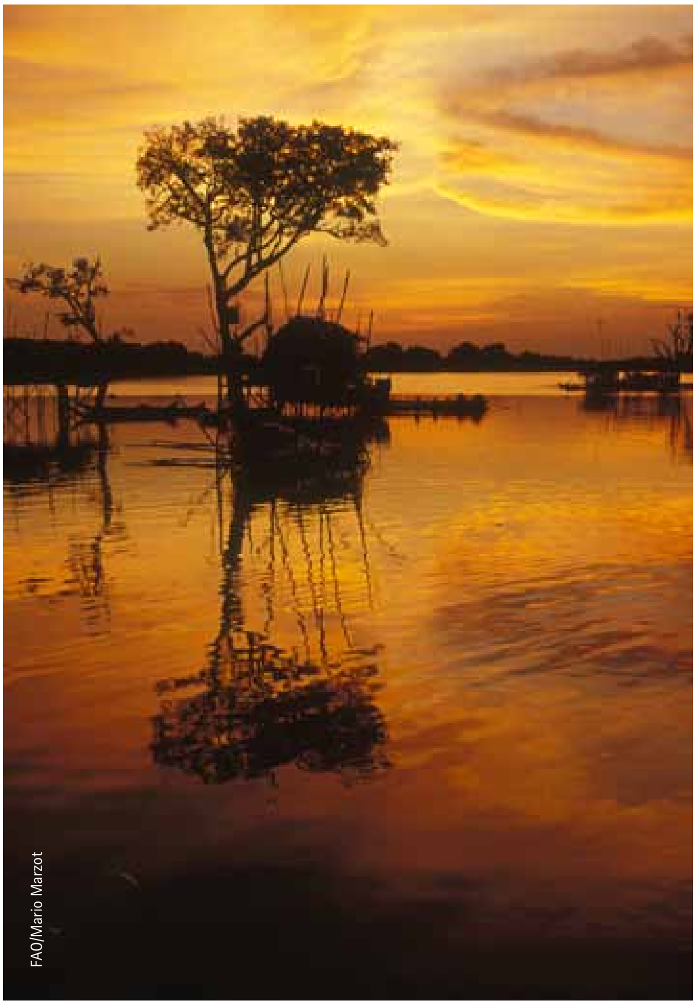


is naturally saline (with fresh groundwater confined at greater depth), since canal seepage here represents a 'non-recoverable loss' contributing to rising water-table and soil salinisation

- on humid alluvial plains with rising water-table in a shallow fresh groundwater system, since excessive canal seepage here will also be contributing to soil water-logging and associated secondary salinisation.

In sharp contrast, on highly permeable alluvial terraces and peneplains (especially in more arid areas) the secondary and tertiary canal systems are often found to carry water for relatively few days per year, and the majority of irrigation users depend entirely on waterwells, but with canal seepage being responsible for much aquifer recharge. This is very explicitly the case in much of the Indian and Pakistan Punjab (Garduno & Foster, 2010). An important corollary is that any attempt to line these canals to 'save water' for use also in other areas can be very detrimental to existing users. However, the implementation of conjuctive management faces significant impediments, which have to be overcome. They are primarily institutional in character, given that provincial government organisations often simply mirror current water-use realities and tend to perpetuate the status quo, rather than offering an enabling structure for promotion of conjunctive management.

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 drawdown stress in some areas.

WHAT IS THE FUTURE OUTLOOK?

The greatly increased utilization of groundwater for irrigated agriculture over the past 20-30 years, and the emerging evidence of widespread excessive exploitation, does not yet represent a 'global resource crisis', but sustainability issues still need urgently to be addressed. In many areas groundwater in natural aquifer storage is capable of 'buffering' over-exploitation for numerous years and providing time for agroeconomic transformation if used intelligently.

The impact of climate-change on groundwater replenishment (and on long-term resource sustainability) remains uncertain, and requires more detailed monitoring and analysis before reliable predictions can be made. But it is clear that groundwater storage reserves will be a critical element in climate-change adaptation to confront more frequent and extended droughts.

Given 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 governance (including institutional capacity and policy formulation) and integrated 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 rather weak. This problem has a number of facets:

- little momentum towards universal metering of larger abstractions and thus inevitable uncertainty over resource use
- restricted dialogue and mutual understanding between agronomists and hydrologists of soil-water balances for irrigated cropping on permeable soils and of seepage from irrigation-canal networks for aquifer recharge.

IWRM – THE CHALLENGE OF 'INTEGRATING' GROUNDWATER

Mobilisation to improve groundwater management and protection needs to be multidisciplinary, strongly participatory and bridge across sectors, and is thus at first sight quintessentially part of the IWRM process (Foster & Ait-Kadi, 2012). Integrated vision and coordinated action at the groundwater-agriculture interface is especially critical. However, for groundwater to be fully 'integrated' some significant challenges have to be overcome:

- 'groundwater bodies' form the spatial framework appropriate for groundwater management, but these have to be reconciled with river basins (the spatial unit for IWRM application)
- decentralisation of water resource administration for IWRM promotion sometimes can spread (often limited) hydrogeological expertise too thinly and 'critical professional mass' needs to be conserved
- senior water managers putting IWRM principles into practice need a much better understanding of groundwater scales, dynamics and vulnerabilities.

These weaknesses need to be remedied to provide a sounder technical foundation for future groundwater management action plans.

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

Increasing farmer incomes from smaller irrigated areas is an attractive option in the quest for

FAO/Rodger Bosch

groundwater resource sustainability – and the rising demand for 'precision irrigation' with pressurised systems offers an adaptable platform for conversion to the intensive cultivation of higher-value crops. 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 licenses or allocations are capped or reduced 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 is likely to remain a very important component of groundwater irrigation in some developing nations. In most cases there exists great 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 have impacts on groundwater recharge through increasing both consumptive groundwater use per unit area and nutrient and/or pesticide leaching. These impacts need to be carefully evaluated, and efforts made to minimise them.

The situation could be further complicated by national strategies to stimulate the cultivation of biofuels (sugarcane, soya beans, maize, etc), requiring groundwater irrigation and increasing the pressure to extend the 'frontier' of irrigation use. But efforts to promote 'virtual water trade' by exporting high water-use crops (such as rice, maize, etc) from wetter to drier countries, could make a valuable contribution towards reducing demand for groundwater irrigation in water-scarce regions.

Principal References

Burke J & Moench M 2000 *Groundwater and society: resources, tensions and opportunities – themes in groundwater management for the 21st Century.* UN-Department of Economic & Social Affairs (New York, USA).

Foster S & Candela L 2008 *Diffuse groundwater quality impacts from agricultural land-use: management and policy implications of scientific realities. Groundwater Science & Policy – an International Overview* RSC Publishing (London, UK) 454-470.

Foster S & Loucks DP 2006 *Non-renewable groundwater resources – a guidebook on socially-sustainable management for water-policy makers.* UNESCO IHP-VI Series on Groundwater 10 (Paris, France).

Foster S & Ait-Kadi M 2012 Integrated Water Resources Management (IWRM) – how does groundwater fit in ? IAH Hydrogeology Journal 20: 415-418.

Foster SSD, Chilton P J & Lawrence A R 2000 *Processes of diffuse groundwater pollution by agricultural land-use*. (in) *Groundwater Contamination and its Control in China*. (ed) Fu R, Yi Q & Shoemaker C A UNEP-SCOPE Publication, Tsinghua University Press (Beijing-China) 1-11.

Foster SSD & Perry CJ 2010 *Improving groundwater resource accounting in irrigated areas: a prerequisite for promoting sustainable use*. IAH Hydrogeology Journal 18: 291-294.

Foster S, Garduno H, Tuinhof A & Tovey C 2009 *Groundwater governance – conceptual framework for assessment of provisions and needs*. World Bank/GWP GW-MATE Strategic Overview Series SO-1 (Washington DC, USA).

Foster S & Steenbergen F van 2011 *Conjunctive groundwater use – a 'lost opportunity' for water management in the developing world ?* IAH Hydrogeology Journal 19: 959-962.

Garduno H & Foster S 2010 *Sustainable groundwater irrigation–approaches to reconciling demand with resources*. World Bank/GWP GW-MATE Strategic Overview Series SO-4 (Washington DC, USA).

Llamas, M R & Martinez-Santos P 2005 *Intensive groundwater use: silent revolution and potential source of social conflicts*. ASCE Journal Water Resources Planning & Management 131: 337-341.

Ostrom E 1990 *Governing the 'commons': the evolution of institutions for collective action*. Cambridge University Press (Cambridge, UK).

Shah T 1993 *Groundwater markets and irrigation development: political economy and practical policy*. Oxford University Press (Bombay, India).

Shah T 2009 *Taming the anarchy: groundwater governance in South Asia*. Resources for Future Press (Washington DC, USA).

Shah T, Villholth K & Burke J 2007 *Groundwater: a global assessment of scale and significance. Water for food, water for life – a comprehensive assessment of water management in agriculture*. IWMI Publication (Colombo, Sri Lanka): 395-423.

Shah T & Verma S 2008 *Co-management of electricity and groundwater: an assessment of Gujurat's Jyoti-Gram Scheme*. Indian Economic & Political Weekly 43: 7: 59-66.

Shah T, Bhatt S, Shah R K & Talati J 2008 *Groundwater governance through electricity supply management: assessing an Innovative Intervention in Gujarat, western India.* Agricultural Water Management 95:1233-1242.

Shah T, Giordano M. & Mukherji A 2012 *Political economy of energy-groundwater nexus in India: exploring issues and assessing policy options.* IAH Hydrogeology Journal (DOI) 10.1007/s10040-011-0816-0.

Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Doell P & Portman FT 2010 *Groundwater use for irrigation–a global inventory.* Hydrology & Earth System Science 14: 1863-1880.

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