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SUSTAINABLE GROUNDWATER EXPLOITATION FOR AGRICULTURE CURRENT ISSUES AND RECENT INITIATIVES IN THE DEVELOPING WORLD

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PAPELES DEL PROYECTO AGUAS SUBTERRÁNEAS

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Stephen Foster graduated from the University of London in 1965, starting his career in geotechnical engineering but moving into hydrogeology at an early stage, with British professional qualification (chartered status) both as an Environmental Engineer and as a Geologist. He has exceptional experience in groundwater research, consulting and advisory work, with a wide variety of practical applications. In addition to Britain he has undertaken professional assignments in more than 35 countries, with major work in Bolivia, Botswana, Costa Rica, Mexico, Peru, Thailand and Sri Lanka. He is author of some 125 published papers, reports and manuals, received a D Sc in 1983 for his published work and awards from British professional societies on five occasions. He has been invited lecturer at many international conferences, served on numerous national and international committees, commissions and boards, and has given intensive courses on groundwater resources evaluation, management and protection in a series of countries.

During 1974-86 he was Groundwater Pollution Research Leader at the British Geological Survey (BGS), being seconded to the World Health Organisation during 1986-89 as Groundwater Advisor for the Latin American & Caribbean Region. He returned to BGS as Chief Hydrogeologist and was promoted to Assistant Director during 1991-99. In 1993 he was also appointed to a Visiting Professorship at the University of London and named as a Foreign Corresponding Member of the Spanish Real Academia de Ciencias. He currently is based at the BGS-Hydrogeology Group at Wallingford in England, from where he is acting as leader of the newly-created World Bank-Global Water Part-nership Groundwater Management Advisory Team.

Stephen Foster is a very active member of the International Association of Hydrogeologists, having led the Burdon Commission for Developing Nations for 10 years from its inception in 1987, having been the Chair-British National Chapter for 1996-99 and having represented IAH (and provided the ground-water dimension) for the World Water Vision Statement & Framework for Action exercise and at the World Water Forum in the The Hague in March 2000.

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ABSTRACT

Groundwater management is among the most important, least recognised and highly complex of natural resource challenges facing society. Major expansion in the exploitation of groundwater resources in many developing nations has brought important benefits to the rural community, including agricultural productivity and improved domestic well-being. However, the rates of abstraction by agricultural users have, in the numerous areas, led to marked degradation of the resource base, in terms of aquifer overdraft and quality deterioration, bringing into question the sustainability of associated rural development. This paper, based on a recent major review (Foster et al, 1999), sets out the context for resource management and describes the technical, institutional, legal and economic approaches that have been adopted in some recent initiatives.

CONTEXT & SCOPE OF ISSUES

Importance of Groundwater for Rural Water-Supply

Groundwater is the fundamental resource allowing the economical and rapid development of more reliable, improved quality, water-supplies for a large proportion of the rural population across extensive areas of Asia, Africa and Latin America (Clarke et al, 1996). This crucial but formidable task begun to gain momentum in the 1980s and has led to significant improvements in quality of life for innumerable rural communities. The continuing challenge is to extend basic services especially in areas with less favourable hydrogeological conditions, and to improve operational sustainability of many systems already developed.

In the African and Latin American context, waterwells have also been of primary importance in the development of extensive livestock rearing in some semi-arid regions. This aspect of agricultural development, however, has not been without its problems because of the tendency to overstock in relation to land capacity in drought years, with heavy over-grazing and soil erosion in the vicinity of livestock watering-boreholes.

During the last 20 years, many nations have witnessed an enormous increase in the exploitation of groundwater for agricultural irrigation. Comprehensive statistics on the use of groundwater for irrigation are not available, but Table 1 provides some relevant data. Groundwater resources have been underpinning the 'green revolution' in agriculture across many Asian nations, and have also permitted cultivation of high-value crops in a significant

Country	Year	Irrigated Area (Kha)	Irrigation water-use (Mm^3/a)
Bangladesh	1990/95	3,750	12,600
China	1993/95	48,000	407,770
India	1990/93	50,100	460,000
Pakistan	1990/91	14,330	150,600
Mexico	1995/97	5,370	61,200
Egypt	1992/93	3,250	45,400
Tunisia	1990/91	310	2,730
Jordan	1991/93	60	740
Irán	1992/93	7,260	64,160
Saudi Arabia	1992/93	1,610	15,300

TABLE 1: **Selected national statistics on agricultural irrigation and groundwater use** (from UN-FAO AquaStat database) the figures do not distinguish supplementary from near-continuous irrigation, nor the type and value of crops grown; they may also inadequately represent conjunctive use which is known to be practised in some areas

number of arid regions with inadequate food production. Groundwater has also provided security against drought in numerous areas where irrigation with surface water resources has been found deficient during dry seasons and dry years, especially at the tail-end sections of irrigation command areas. The interaction and interdependence of groundwater and surface water resources is such as to greatly favour their conjunctive use in agriculture, despite the institutional barriers that often impede its promotion and development.

It is most important to record that the use of groundwater can be a major factor in promoting increased irrigation water-use efficiency and productivity, because the energy costs associated with pumping are much higher than for surface water. This provides the incentive to increase water conservation and/or to irrigate higher-value crops. Moreover, the scale of groundwater development has facilitated tubewell ownership/operation at the

Country	**Origin of water**	
	surface (%)	**ground (%)**
Bangladesh	31	69
China	78	18
India	41	53
Pakistan	66	34
Mexico	73	27
Egypt	96	4
Tunisia	39	61
Jordan	40	55
Irán	50	50
Saudi Arabia	3	96

TABLE 1: *Continuation.*

level of individual farmers or small collective groups, and this has allowed greater flexibility of irrigation scheduling, much simpler command areas, and responsibility for operation and maintenance to be devolved.

However, the rapid development of groundwater has led to a proliferation of waterwells of lower constructional standards, which may compromise both water source reliability and water resource availability (due to storage overdraft and quality degradation). Overall the sustainability of the groundwater resource base is critical for an array of basic human needs from public health to poverty alleviation and economic development (Kahnert & Levine, 1993; Clarke et al, 1996).

Evolution of Socio-Political Perspectives

Groundwater exploitation is not new, but abstraction on the large-scale is. Wells have been excavated ever since pre-historical times, but the potential for groundwater exploitation changed radically as advances in rotary drilling technology, in the turbine pump and in geological knowledge spread, most notably during the 1960s and 1970s. Early techniques had very limited abstraction capability and by comparison resources appeared infinite. The situation has changed drastically, but perception lags considerably behind reality.

In some cases, governments have encouraged groundwater development to meet the needs of rural populations as a mechanism for increasing their political popularity, regardless of consideration of the status of the resource base. For example, virtually all Indian government organisations concerned with groundwater were developed to promote resource exploitation rather than resource management; well drilling and pumping energy remain highly subsidised despite widespread evidence of aquifer storage overdraft. Such patterns have been repeated in many countries worldwide.

The challenges inherent in this history are compounded by the increasingly critical role groundwater resources play in the livelihoods of individual users in many developing nations. Access to groundwater for irrigation is making a very positive impact on subsistence and income for poor farmers, and in many cases also reduces the need for the rural poor to migrate during droughts by increasing their income security. These direct individual benefits make any subsequent constraints on groundwater use politically sensitive. In combination these factors represent both a cause of groundwater management problems and an obstacle to the implementation of effective responses.

INDIA

Groundwater is central to rural development and food security in India, with over 50% of the irrigated area and some 85% of drinking water being supplied from waterwells. Moreover, access to groundwater reduces agricultural risk and enables poor farmers to invest and to increase production. Development of groundwater resources in India proceeded rapidly and the increases in abstraction have had a major impact on the resource base in many arid and hard rock regions. Nationwide, the number of administrative 'groundwater resource blocks' classified as fully or excessively exploited reached 383 in 1992-93. The emerging groundwater resource problems closely relate to high governmental subsidies in the agricultural sector. The subsidy on power supplies is perhaps the most significant, since in most states electrical energy is provided at a flat annual rate, based on pump capacity and in some it is provided free of charge. Official estimates indicate that power consumption in agricultural exceeds 40% of total energy use in many areas.

Addressing groundwater overpumping in India is complex. While centralised regulatory arrangements have existed since the 1970s, it is questionable whether they can be implemented given the millions of individual well owners on small landholdings, the inadequate administrative set-up and that reduction in subsidies generates strong political opposition. Nevertheless, some states (such as Rajasthan) are building groundwater management capacity by investing in data collection and the development of user-based management organisations in a series of groundwater resource conservation zones. In Andhra Pradesh and Uttar Pradesh various measures have been taken:

- reduction in energy subsidies and reform of pricing structures
- prohibition of drilling deep tubewells for irrigation
- mandatory construction of streambed groundwater recharge structures
- introduction of economic incentives for dryland (as opposed to irrigated) cropping.

Moreover, regulatory agencies in developing nations are nearly always under resourced and often weakly empowered in relation to the control of groundwater abstraction. However, increasing their financial budget and strengthening their legal provision will not necessarily improve the situation. Certain inherent factors also need to be addressed:

- the highly-dispersed nature of groundwater abstraction, combined in many countries with deeply-entrenched traditions giving individual landowners abstraction rights
- the uncertainty of resource evaluation due to hydrogeological complexity and meteorological variability, and to inadequate monitoring of aquifer system response to abstraction
- the pressure for resource exploitation regardless of long-term consequences, sometimes exerted by politically-powerful land owners and/or plantation enterprises
- the lack of public and political awareness of the potentially-irreversible consequences of excessive groundwater exploitation, and thus absence of an adequate consensus for action.

The economic characteristics of groundwater have also played a major role in the emergence of management problems and represent significant obstacles to the development of management responses. Groundwater is generally undervalued, especially where exploitation is uncontrolled. In this situation the exploiter of the resource, in effect, receives all the benefits of groundwater development, but (at most) pays only part of the costs, usually the recurrent costs of pumping (although even energy supplies may be subsidised) and sometimes the capital cost of well construction, but never the associated externality costs (such as reductions in stream baseflows, saline intrusion, impacts on wetlands, loss of strategic groundwater storage in extreme drought) (Figure 1).

Moreover, in economic terms groundwaters (like fish) are a resource for which property rights are not naturally and obviously defined in a legal sense. Thus, except in those nations where clear rights systems have been implemented, groundwater would still be termed a common-property resource. In this situation individual users have little ability to conserve groundwater for their own future use. Even where the finite nature of the resource is recognised, users often lack understanding of resource dynamics, aquifer boundaries and potential contamination.

Undervaluation leads to economically-inefficient patterns of groundwater allocation and use. In many cases groundwater is allocated to low value uses (such as the production of grain or fodder crops in arid regions), while higher value uses (such as provision of safe drinking water) are only partially met. In addition, because in-situ values associated with groundwater are rarely reflected, undervaluation stimulates overexploitation, by reducing incentives for investment in water conservation and (more generally) in resource management.

Evidence of Degradation of Groundwater Resource Base

All groundwater exploitation by wells results in some decline in aquifer water-level (water table or piezometric surface) over a certain area. Some reduction can often be considered not only as ne-

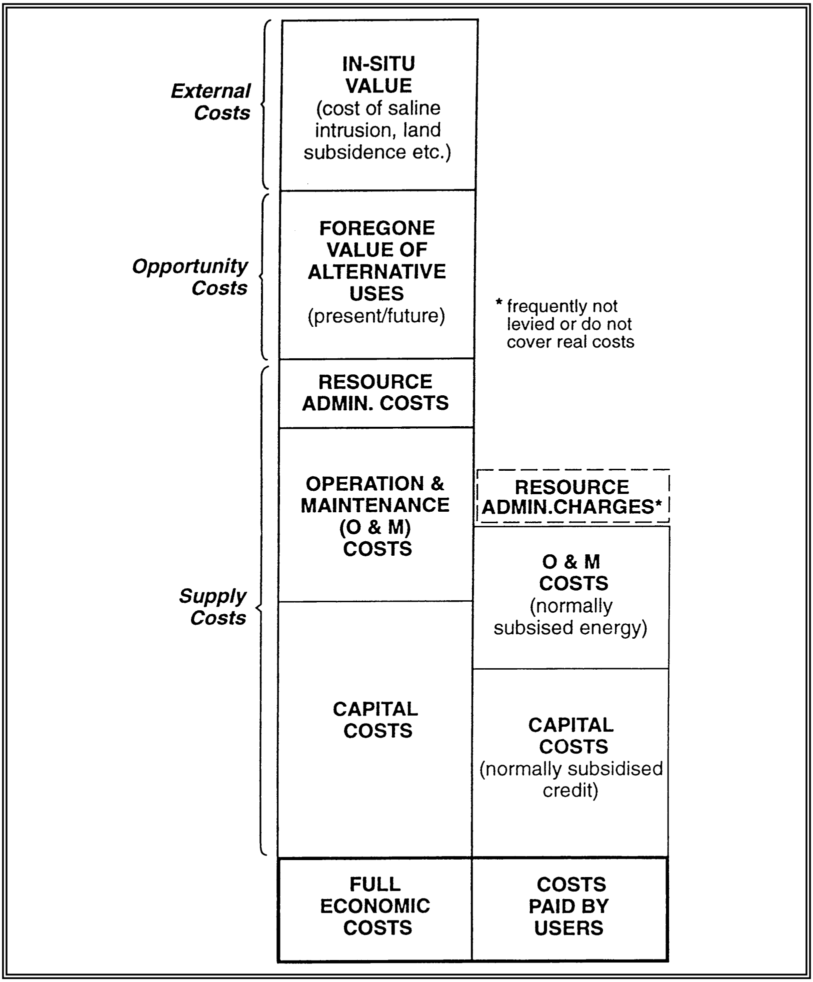


FIGURE 1: **Measuring the costs of groundwater use** *in all cases those paid by the users represent only a minor proportion of the full economic cost.*

cessary, but also desirable, since it often improves land drainage and maximises groundwater recharge rates, by providing subsurface storage space for the infiltration associated with high rates of excess wet-season rainfall (Kahnert & Levine, 1993).

However, if the overall abstraction from part or all of an aquifer system exceeds the long-term average rate of replenishment, there will be a continuous long-term decline in water level, overdraft of aquifer storage and consumption of aquifer reserves. The same essentially can apply to abstraction from a deep semi-confined aquifer in which the limiting factors will be:

- the rate of leakage which can be induced to flow through the confining beds from overlying shallow aquifers
- the rate of replenishment of the shallow aquifers from surface infiltration.

This overdraft of aquifer storage can have series of consequences (Table 2) (Custodio, 1992; Foster, 1992). These include reversible interference with wells and springs, but can also include quasi-irreversible aquifer degradation, due to ingress of saline or polluted water. Significant reversible side-effects (such as well pumping-cost increase and well yield reduction) occur if an excessive number of boreholes are drilled in relation to the available resource and its optimum exploitation pattern, and this can be particularly marked where the hydraulic structure of an aquifer is such that its most productive horizons occur at shallow depth and are thus prone to early dewatering (Figure 2).

More serious are the near-irreversible side-effects (Table 2), especially those involving the encroachment of saline water which is becoming increasingly common. This may intrude laterally from the sea, if coastal hydraulic gradients are reversed (Figure 3), but also rather commonly occurs from above in layered coastal aquifers (Foster & Lawrence, 1995). These often have natural upward hydraulic gradients which reverse with heavy exploitation of deeper freshwater horizons. These effects are quasi-irreversible, since the saline water which first invades macropores and fissures, diffuses rapidly into the porous aquifer matrix under the prevailing high salinity gradients. It will then take decades to be

CONSEQUENCES OF EXCESSIVE EXPLOITATION		FACTORS AFFECTING SUSCEPTIBILITY
Reversible Interference	· pumping lifts/costs increase · borehole yield reduction · springflow/baseflow reduction	· aquifer response characteristic · drawdown to productive horizon · aquifer storage characteristic
	· phreatophytic vegetation stress (both natural and agricultura) · aquifer compaction/transmissivity reduction	· depth to groundwater table · aquifer vertical compressibility
Irreversible Deterioration	· saline water intrusion · ingress of polluted water (from perched aquifers or rivers) · land subsidence and related impacts	· proximity of saline/polluted water · vertical compressibility of overlying/interbedded aquitards

TABLE 2 : **Consequences of excessive groundwater exploitation** *the two effects in the middle band above maybe either reversible or irreversible depending on local conditions and the period during which excessive groundwater abstraction persists.*

flushed out, even after the flow of freshwater has been re-established. The ingress of saline water is terminal for virtually all uses, and has also quite widely resulted in damage to soils, where farmers continue to irrigate with increasingly brackish water in an attempt to obtain a return on their investment in waterwells.

More widespread is the incidence of competition for available groundwater resources with the result of water-tables falling in excess of 1.0 m/a. Even in the extensive thick alluvial and sedimentary inland aquifers of the more humid climatic regions,

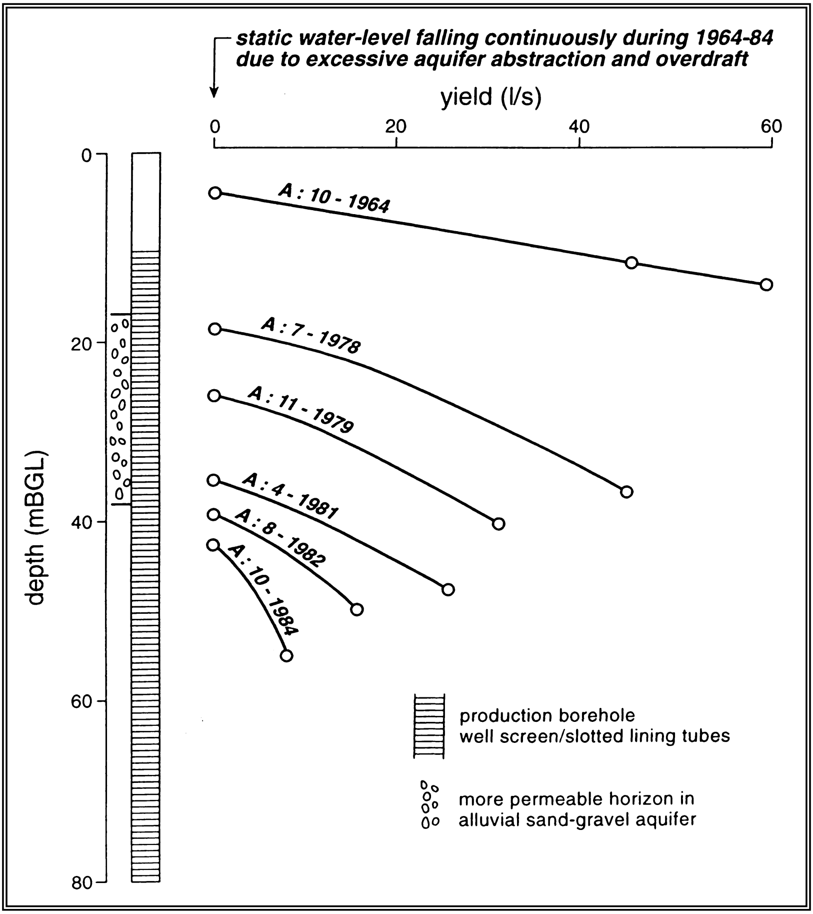


FIGURE 2 : **Historical evolution of operational performance of a production borehole in a heavily-overexploited alluvial aquifer** *as a result of dewatering of the most productive horizon maximum yield reduced from 60 to 10 l/s while pumping lift increased from 15 to 55 m during 1964-84.*

there is evidence of increasing social inequity where deeper, larger-capacity, irrigation boreholes lower the regional water-table and increase the cost of (or eliminate the access to) water-supply for users of shallow domestic wells (Figure 4) (Macdonald et al,

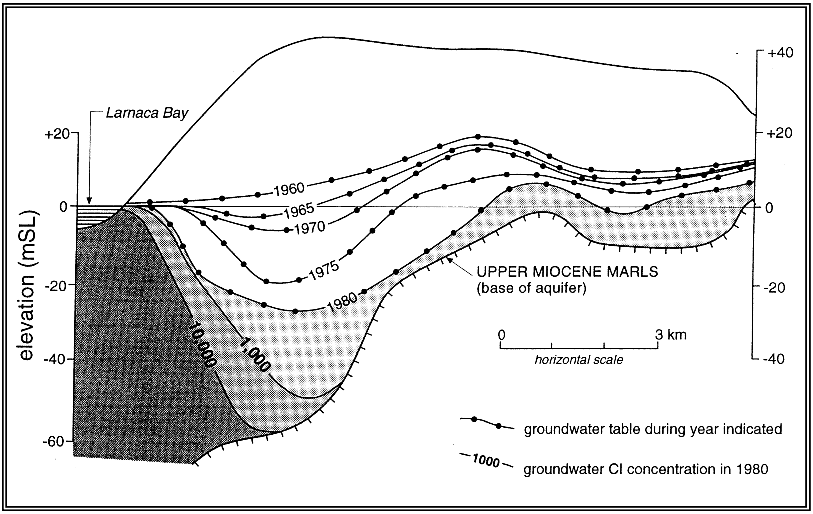


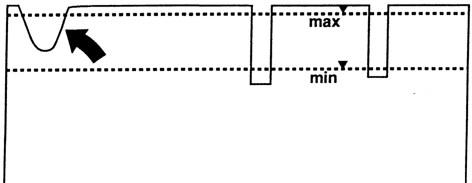
FIGURE 3: **Groundwater storage reduction in the Tertiary limestone aquifer of southeastern Cyprus due to intensive uncontrolled development for agricultural irrigation** *over a 20 year period major reduction in the available saturated aquifer thickness has occurred as a result of both water-table decline and saline intrusion.*

1995). In the long run, all of these processes call into question the sustainability of existing agricultural exploitation of groundwater and thus the security of food supplies provided by such irrigation.

Variability of Resource Constraints and Exploitation Scale

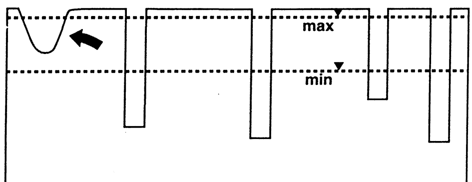
Local hydrogeological conditions impose constraints on the access to groundwater for rural development and have major implications for development costs. It should be noted that such constraints range from absolute in terms of large-scale groundwater development for irrigation in certain environments, to minimal in more favourable hydrogeological environments as regards domestic/livestock waterwell drilling.

YEAR	no. of wells (M)	average well abstraction (m^3/d)	est. total abstraction (Mm^3/d)
1960	0.55	70	38



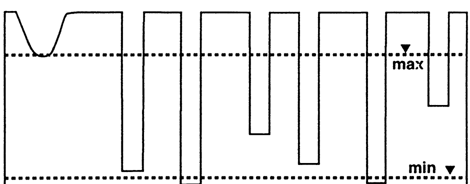
- limited groundwater abstraction (few wells/animal power/some diesel pumps)
- significant baseflow to streams

1970	0.70	100	70
1980	0.85	150	128



- increased groundwater abstraction (additional wells, diesel/electric pumps) and many wells deepened
- reduced baseflow to streams

1990	1.25	230	276



- further major increase in abstraction (electric pumps) with all wells deepened
- no baseflow discharge to streams

FIGURE 4: **Historical development of the Deccan Traps groundwater system in Maharastra-India** *the total abstraction increased 7-fold in a 30-year period as a result of both the spread of motorised pumping plant and well drilling, but this led to intense competition for the available groundwater resources and virtual elimination of baseflow to local streams*

The scale of groundwater exploitation determines the extent of potential external impacts and thus the need for proactive resource management (Figure 5). The likelihood of encountering serious problems of resource overexploitation relates almost exclusively to groundwater supply for agricultural irrigation, since for rural domestic and livestock water supplies resource sustainability issues are only significant for shallow low-storage aquifers in the more arid regions during extreme drought.

Other Linkages between Groundwater and Agricultural Development

The introduction of irrigated agriculture causes major modifications to the soil moisture regime, and generally results in substantially increased infiltration. While not all soil infiltration necessarily results in groundwater recharge to deep aquifers, excess irrigation is a major source of groundwater recharge and under arid conditions deep infiltration may be reinitiated where little has occurred in decades or centuries. In these more arid situations, and under hydrogeological conditions which do not support the development of regional aquifer flow systems, excess irrigation is likely to be the dominant component of local aquifer recharge. This, of course, is regardless of whether the main source of irrigation is surface water or groundwater resources, although in the latter case, the effect of the increased recharge will be masked in the response of the water-table. The corollary, however, is that if irrigation efficiency is increased groundwater recharge decreases - a correlation which is often overlooked in catchment-level water management plans.

Groundwater recharge from irrigated agriculture occurs by various mechanisms;

- directly from unlined (and in some cases lined but leaky) primary and secondary canals, and even from some agricultural drains

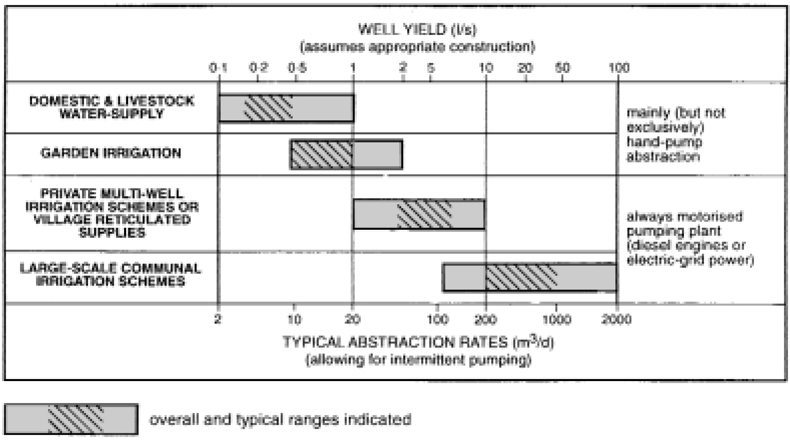


FIGURE 5: **Variation of yield and abstraction requirements for different types of rural groundwater use** *those yields which do not require motorised pumping plant do not threaten groundwater resource sustainability and thus need only minimal regulation; they do, however, benefit from systematic hydrogeological investigation and engineering construction protocols*

- directly from irrigation water distribution systems below this level
- through over-irrigation at field level.

It should be noted that the potential for groundwater recharge from irrigated agriculture varies considerably across and along irrigation areas. In low-lying areas, or where the soil profile has low permeability horizons, rising water level or shallow perched water bodies are likely to develop. This ultimately leads to soil water-logging and salinisation through direct evaporation, unless drainage is introduced to remove excess groundwater.

The fact that in many areas a large proportion of groundwater recharge originates as infiltration on agricultural land also has a negative side - namely the risk of excess leaching of nutrients and pesticides. A close correlation commonly exists between agricultural development and groundwater quality in underlying phreatic aquifers. In practice, the rates of leaching will vary widely with cropping regime, soil-type and hydrogeological conditions (aquifer vulnerability); irrigation water efficiency and the continuity of crop coverage are especially critical factors (Foster & Chilton, 1998). In certain monocultures on permeable soil profiles, especially those involving soil ploughing and fallow periods, the leaching losses maybe severe.

The principal impact is on the potability of groundwater for rural water-supply at farm, village and small town level. While it is not the subject of this paper, it should be noted that rurally-sited potable groundwater supply sources often require protection from agricultural soil leachates. The rational approach would be to define their capture area through hydrogeological studies (Foster & Skinner, 1995), and consider imposing some constraint on the use of agricultural fertilisers, manures or pesticides, or even the cropping regime in part or all of these areas, depending on the vulnerability of the aquifer system involved. This is not easy, but may be achieved by voluntary agreement with farmers, through payment of compensation for agricultural crop losses or through land purchase by the water-supply undertaking with farming (or other use) under a leasehold system with appropriate constraints.

On the other hand, it is rare that the level of contamination of groundwater from agricultural practices can prejudice its use for agricultural irrigation itself, except in a few cases of exceptionally severe nutrient and/or pesticide leaching in an area of cultivation of highly-sensitive crops. Along with nitrate and pesticides, there is considerable leaching of salts from irrigated agricultural soils and in extreme cases (where major groundwater recirculation occurs) this fractionation can cause a troublesome quality impact. Thus, in areas of major development of irrigated agriculture from groundwater in arid climates, it is as important to investigate and model the salt balance, as it is the water balance.

HYDROGEOLOGICAL FRAMEWORK FOR RESOURCE MANAGEMENT

Clarification of Some Key Concepts

Groundwater Resource Overexploitation

Groundwater overexploitation is an emotive expression which is not capable of rigorous definition (Foster, 1992; Llamas, 1998). However, groundwater scientists and water resource managers would be wise not to abandon the term since it has clear register at the political level.

For groundwater exploitation to be regarded as sustainable, the constraints imposed by aquifer recharge rates must be respected, albeit that there may be serious difficulty in estimating these with adequate precision. A number of significant difficulties are often encountered:

- over what area should the groundwater balance be evaluated, especially in situations where pumping is very unevenly distributed
- for what period should this balance be evaluated, especially in the more arid climates where major recharge episodes may occur as infrequently as once a decade or even once a century
- more general uncertainties about aquifer recharge mechanisms and rates as a result of inadequate field data, including the increase of recharge sometimes associated with a lowering water-table and the effect of accelerated climate-change phenomena.

In practice, we are more concerned about the consequences of heavy abstraction than its absolute level, and the most useful definition of aquifer overexploitation is probably an economic one: namely, that the cost of the overall negative impacts of groundwater exploitation exceeds the net benefits of groundwater use

(Young, 1992). Thus the way in which the situation is interpreted will vary with the exploitable storage of the aquifer system and its susceptibility to side-effects during short-term overdraft. It is not widely appreciated that differing hydrogeological environments and aquifer types exhibit widely varying susceptibility to the side-effects of excessive abstraction.

Aquifer Safe Yield

A realistic conceptual model with estimates of the mechanisms and rates of aquifer discharge (as well as recharge) is also a prerequisite for groundwater resource management. This is inevitably aquifer specific, but the results will not only provide a cross-check on recharge estimates and reveal key linkages to the surface water environment which are dependent upon the groundwater flux of the aquifer system concerned (Figure 6). It is important to distinguish:

- discharge to freshwater systems, since these may be required to sustain downstream uses for water-supply interests and/or other river interests
- discharge via natural vegetation, including sustaining ecologically and/or economically valuable freshwater wetlands and brackish lagoons
- discharge to saline areas including coastal waters, salt lakes and playas.

Since all groundwater flux in an aquifer must be discharging somewhere, the question of the safe yield for groundwater exploitation arises. This should be recognised as an essentially subjective concept. Safe yield is obviously bounded at the upper level by the long-term active aquifer recharge rate, however, it should (but all too frequently does not) involve value judgements about the importance of maintaining (at least a proportion of) some of the discharges from the aquifer system. This is not straightforward, but it is obviously essential that the resource evaluation process should at least identify all downstream linkages and dependencies.

Irrigation Demand and Real Water Savings

The fact that excess irrigation often represents an important component of groundwater recharge, and thus in turn will be available to other local groundwater users or form discharge from the aquifer as baseflow in downstream rivers, has already been mentioned. It follows that while increasing irrigation water efficiency will generally represent a «real energy saving» (since less pumping will be required), it does not necessarily or generally represent a «real water saving».

Only those modifications to irrigation and cropping practices that reduce non-beneficial evaporation and evapotranspiration or water losses to bodies of saline water actually represent 'real water savings'. The former include soil evaporation from between crop rows, evaporation from the irrigation distribution system, evapotranspiration by the crop itself which is not effective in producing yield, increased direct phreatic evapotranspiration by unwanted vegetation, evaporation during spray irrigation, etc. In rural areas these should be the primary targets for demand management aimed at conserving groundwater resources, and over extensive areas of the North China Plain, for example, it is believed that more than 100 mm/a can be saved in the irrigation of the annual winter wheat/summer corn cycle.

Relevance of Aquifer Characterisation

A key message of this paper is that the natural hydrogeological environment exerts the dominant control over availability of groundwater resources for any type of rural development and corresponding water-supply development costs and difficulties. Geodiversity, in general, and hydrogeological variability in particular, are still poorly appreciated by many working in water and land resource management and in promoting rural development projects. There is thus great need that they recognise intrinsic

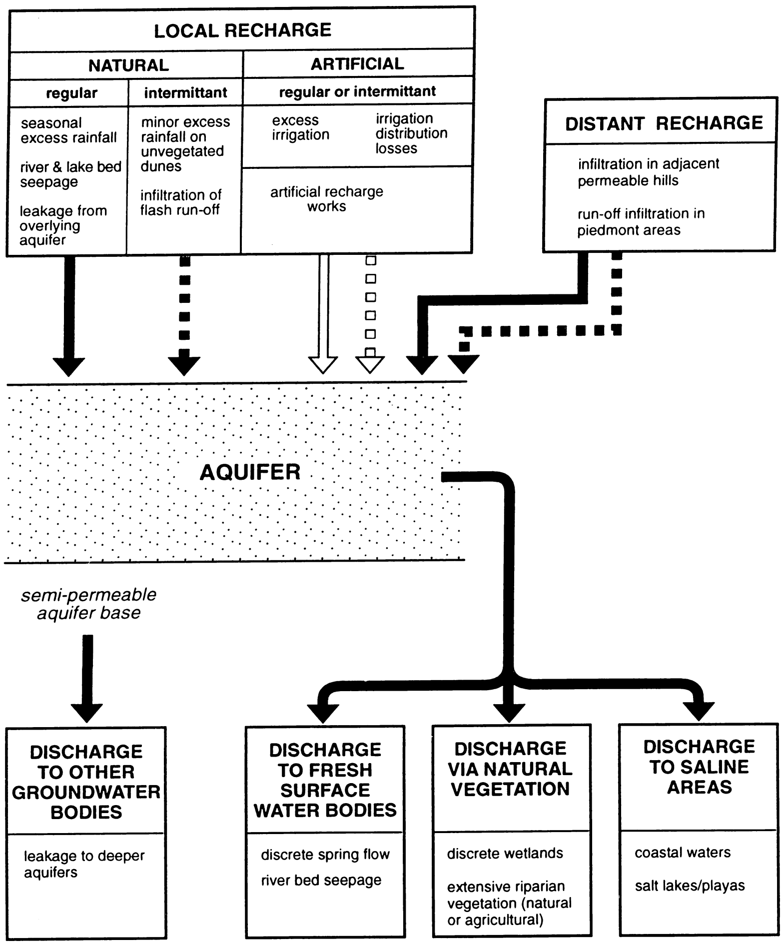


FIGURE 6: **Classification of principal mechanisms of groundwater recharge and discharge** *this applies to an essentially unconfined aquifer system, but not all components will be significant in every case.*

constraints on groundwater development, and try to work with nature rather than against it, when identifying and promoting groundwater development schemes.

The estimation of groundwater recharge rates is a key activity in appraising the sustainability of current and future aquifer development. Recharge quantification is fraught with significant technical problems, data deficiencies, and resultant uncertainty (Lerner et al, 1990; Simmers et al, 1997) because of:

- the wide spatial and temporal variability of rainfall and runoff events, especially in the more arid regions
- the widespread lack of lateral uniformity in soil profiles and hydrogeological conditions.

To reduce uncertainty it is necessary to apply and to compare a number of independent techniques, the application of which will be constrained to varying degrees by the ambient field conditions.

For most practical purposes it is sufficient to make approximate estimates, and more precision can only be achieved through the analysis of carefully-monitored aquifer response to significant medium-term abstraction. However, the frequency of infiltration events and the vadose zone transit time until recharge reaches the water-table are also important considerations.

A number of useful general observations can be made in relation to aquifer recharge:

- there is no doubt that recharge occurs, to some extent, even in the most arid regions, although areas of increasing aridity will be characterised by much decreased downward flux to the water-table of much greater temporal variability as aridity increases, direct rainfall recharge will become less important in terms of total replenishment than indirect runoff recharge, and the artificial (or incidental) recharge arising from human activity becomes increasingly significant (Figure 6)

- estimates of direct rainfall recharge are always likely to be more reliable than those of indirect recharge from runoff.

The evaluation of groundwater resources must not stop with the estimation of currently-active recharge rates. It is of equal importance to identify the linkages with land-use and surface water, especially in arid regions where a major proportion of the total recharge may be derived from irrigation canals and/or irrigated fields. Modifications to canal construction and operation, irrigation technology and cropping regimes can then cause radical changes in groundwater recharge rates.

Beyond the development and quantification of a sound conceptual model of aquifer recharge and discharge, a key requirement in groundwater resource evaluation is assessing the volume of exploitable aquifer storage and the susceptibility of the aquifer system to adverse side-effects if subjected to either short-term (temporary) or long-term overdraft due to excessive pumping. In many ways the vast storage of many groundwater systems is their most valuable property, and this needs to be exploited in a strategic fashion. The key question is how to use, but not to abuse, this storage resource. This should depend on the relative value of the services provided by maintaining groundwater levels compared to the value of deeper groundwater storage and the susceptibility to resource exploitation-related side-effects. It is important for cost-effective groundwater and land management to diagnose this susceptibility adequately. The most critical factors in determining the severity of reversible and irreversible effects respectively is the available drawdown to the most productive aquifer horizon and the proximity of a saline-water interface.

The value of an integrated operational approach to refining the evaluation of groundwater recharge and storage cannot be overstated. In this context it is vital that sufficient effort goes into monitoring aquifer response to ensure that adequate data are collected. Short-term economies in this respect are likely to prove counterproductive in the long run. In areas of complex hydrogeology, this approach will be the only practicable way to improve the reliability of groundwater recharge estimates and in many less complex situations it will often still be the most cost-effective way. It is also important that synoptic data of aquifer evaluation and groundwater status are systematically disseminated in suitable form to the principal stakeholders and the general public.

BANGLADESH

Bangladesh has an urgent need to augment food grain production to alleviate rural poverty. The availability of land in the dry season means that irrigation from groundwater is economically attractive and provides the quickest route to achieve these policy goals. Groundwater development for irrigation commenced in the early 1970s and reached an area of 7,300 km^2 by 1985. Initially it was financed and operated by public sector institutions using high-yielding deep tubewells which provided water to rural landowners, but from 1975 there was a major increase in privately-owned, low-cost, shallow tubewells equipped with surface suction-lift pumps powered by diesel engines. By 1985, it was estimated that 173,500 of these were operating, together with 285,400 manually-operated shallow tubewells, compared to only 17,200 deep tubewells, since farmers prefer the smaller units which involve less dependence on water purchase. However, shallow tubewells with suction lift pumps can only raise water from depths of 6-8 metres and the absence of a significant monsoon in 1983 (believed to be a 1-in-25 year event) lead to failure of these water sources in some areas and raised doubts about the appropriateness of this technology.

Under natural pre-development conditions the complex layered alluvial/deltaic aquifer of Bangladesh has groundwater levels virtually at the surface during the wet season with a recession down to 3 metres depth by the end of the dry season. This means that much potential recharge is rejected, and infiltration of rainfall to groundwater can be increased from 150-200 mm/a to 400-500 mm/a if the water-table is lowered by abstraction for irrigation. The degree of water-table lowering will depend on the proportion of the land area irrigated in the dry season and the specific yield of surficial strata experiencing drainage. In areas where the latter is high, it is possible to maximise (and to access) all potential recharge with shallow tubewells powered by suction-lift pumps. In such areas deep tubewells should be discouraged as being less economic and potentially conflictive. However, in other areas deep tubewells with lineshaft pumps are required and the water-table may be drawn down to 10-15 m by the end of the dry season, which can cause serious interference with shallow tubewells. Modified shallow tubewells with lineshaft pumps, capable of yielding 5-10 l/s from up to 11 m depth, are now being developed for such areas.

INSTITUTIONAL, LEGAL & ECONOMIC APPROACHES

Mobilising Stakeholder Participation on Resource Management

In most cases, addressing groundwater overexploitation requires demand-side management – changes of individual use for irrigation that reduce total abstraction. These changes need to occur in activities that take place daily and affect both livelihoods and lifestyles. Users must, as a result, play a paramount role in management and groundwater regulators need to work collaboratively with them in setting objectives and in formulating strategy. Collaboration must involve a dialogue between groundwater regulators and local stakeholders (Figure 7) in which all parties have some power to determine courses of action. This is of fundamental importance, since in many cases a gulf exists between the approaches advocated by government authorities and the perceptions of local users (Moench, 1994).

Management tensions also result from the fact that state administrative units, settlement patterns and cultural groupings ra-

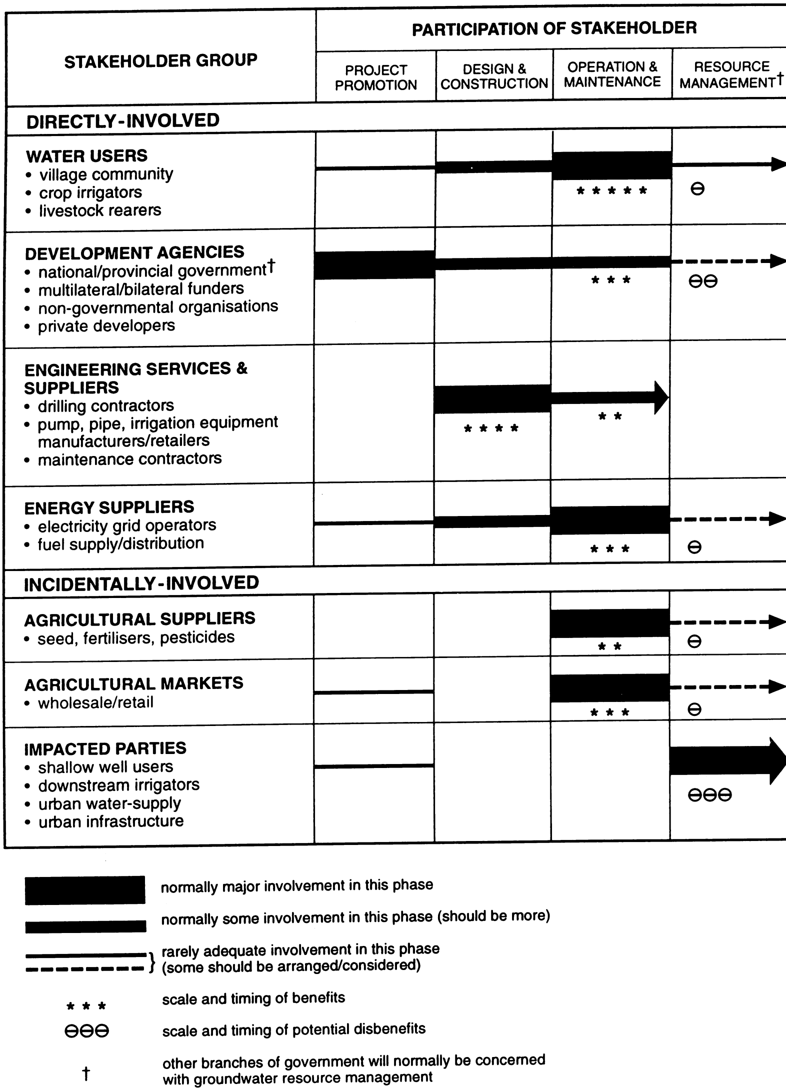


FIGURE 7: **Analysis of actual and required stakeholder participation in rural groundwater development for agricultural irrigation** *both the typical current situation and the preferred approach is indicated*

rely correspond to the boundaries of aquifer systems. State organisations operate at a large-scale and find it difficult to address the highly-localised factors governing groundwater use. At the same time, community groups (water user associations), while being effective in local water allocation, lack the regional perspective and influence (Subramanian et al, 1997) essential to address aquifer management needs. Highly-dispersed use patterns can have significant aggregate impacts, but the problems often arise at substantial distance from many users. The migration of a saline water front for example, is often due to changes in groundwater flow caused by regional pumping patterns, but the only users affected are those in the specific area where saline water intrudes.

In all countries there is likely to be significant variability in the hydrogeological factors controlling groundwater resource availability and the socioeconomic factors affecting their use for agricultural irrigation. These sets of factors interact and result in a groundwater resource management context that can vary greatly between locations. It is thus necessary to develop management approaches that can be tailored closely to specific situations, and can adapt effectively as the larger socioeconomic context changes.

In general, the institutional framework shaping groundwater management options can be viewed as comprising four possible levels:

- the macro high-level comprising social norms/rights and legal principles
- state organisations, market institutions and rights structures operating at provincial level
- intermediate level organisations operating at hydrological unit level
- local institutions operating at the level of groups of users or communities.

Enabling groundwater management to occur requires institutional arrangements at several of these levels (Table 3). Local conditions often cannot be addressed in the absence of a higher-level enabling framework. As a result institutional arrangements for groundwater management inherently involve multiple levels, and need to tiered.

In most situations there is a major gap at the intermediate institution level. National water laws generally exist and in many cases articulate basic principles clearly. State regulatory agencies also often exist, though their capabilities vary greatly, but there is a gap between these organisations and the level of community groups and local users. This is leading to the development of 'aquifer management committees', with representation of various water user associations, municipal water companies, industrial groundwater abstractors and the provincial regulatory agency or government ministry.

Definition of Groundwater Rights

The regulation of groundwater resources is a many-facetted process which is best carried out on a flexible and adaptive basis though the collaborative efforts of some form of local regulatory agency, aquifer management committees and local water-user associations. Amongst the key activities needed are the establishment or consolidation of a register of abstractors and the organisation of water abstraction rights.

Some form of rights system related to groundwater abstraction will be present in most situations. In some cases, however, such rights are only informally established on the basis of social practice, whereas in others they are formally registered and encoded in law. In many situations, the clarification of groundwater rights (and in certain instances rights reform) is an essential prerequisite to the introduction of management measures. It is important to emphasise that water rights systems are not inherently dependent on government agencies or legal systems, but can be carried out through social processes. In some ways active self governance is in the long-run preferable to the imposition of government rules.

MEXICO

In Mexico more than 100 aquifers have been declared seriously overexploited. These are mainly in the central and northern parts of the country, where well depth and pumping costs have increased many fold since 1970 and groundwater levels are falling by up to 5.0 m/a. Following the new Mexican Water Law of 1992 various steps have been taken:

- registration of all waterwells (including illegal ones) with some 66,000 concessions approved
- introduction of a 'water rights fee', although abstraction charges remain low and inconsistent, with the continued exemption of the agricultural sector being highly anomalous
- establishment of 'water rights markets' in some areas with the regulatory agency holding a list of selling offers.

A comprehensive study of the incentives and disincentives for individual stakeholders in relation to groundwater resource overexploitation has been undertaken. This, together with hydrogeologic and socioeconomic modelling of various management scenarios, has led to the following proposals:

- strengthening of aquifer management committees through finance mechanisms, capacity building and function transfer
- building public awareness of the resource situation to build a consensus for action
- improving monitoring networks (selective abstraction metering, aquifer piezometric levels, water-use patterns, etc) to provide more relevant data for management

- retargeting the electrical energy subsidy to eliminate any incentive for aquifer overexploitation
- addressing the need for progressive reduction of water rights in many 'overallocated aquifers', including the need for financial support on water-saving technology.

Regulatory functions are central to groundwater management in all situations where the characteristics of the groundwater resource are not such as to be effectively self-regulating, and especially where the risks of irreversible degradation are significant. However, direct regulation is often extremely difficult because of the large number of geographically-dispersed abstraction points involved. Additionally, unless broad social support exists for regulation, enforcement is often politically problematic. Thus while a broad regulatory framework is required to provide the platform on which other management approaches operate, it is rarely effective by itself.

In the case of direct regulation by an agency of local government, experience suggests this will be more successful where good relations have been built-up with those drilling waterwells, by (for example) providing hydrogeological advice. Exercising control over the construction of wells themselves - their numbers, depths and diameters - is the most effective route to controlling groundwater abstraction. Public relations are extremely important and both water users and the general public need to be kept informed of the state of groundwater resource exploitation and the benefits of sound resource administration.

Role of Water Markets

Informal water markets are fairly widespread in developing nations. These markets generally involve local transactions between well owners and other users adjacent to each well. They func-

KEY FUNCTIONS	POTENTIAL ACTIVITIES
Resource Evaluation	· assessment of status of groundwater resource exploitation · targeted monitoring of groundwater levels and quality
Strategic Planning	· integrated analysis of socioeconomic roles/interactions of groundwater · coordination with government/private sector institutions directly/indirectly related to groundwaterpro/imp
Identification of Management Priorities	· assessment of susceptibility to degradation · identification of resource conservation zones · groundwater valuation and pricing reviewpro
Resource Regulation	· establishment/consolidation of register of abstractors, abstraction rights and water charges/markets · water (re)allocation and dispute resolution · demand management support · compliance monitoring and enforcement measures

NPM: national planning ministry
RRA: provincially-based regulatory body
AMC: aquifer management committee
WUA: water-uses association

pro: promote
inv: involve
imp: implement
inf: inform

TABLE 3: **Summary of key groundwater resource management functions and corresponding instituional responsibilities** *this gives a general indication of the tiering of roles corresponding to institutional competence and scale/level of operation.*

tion on the basis of informal (but socially accepted) agreements, and involve transfers of water but not of water rights . These water markets are fundamentally different from those functioning formally on the basis of trading in legally-defined volumetric water rights.

Both types of water market communicate a portion of the economic value of groundwater to both buyers and sellers. Within

KEY FUNCTIONS	INSTITUTIONAL ROLES			
	NPM	RRB	AMC	WUA
Resource Evaluation	pro	imp/inv	inv/inf	inf
		pro/imp	imp/inv	inf
Strategic Planning	pro/imp	inv	inv	
	pro/imp	inv	inv/inf	
Identification of	pro	imp	inv/inf	inf
		pro/imp	inv	inf
	pro/imp	imp	inv	inf
Resource Regulation		pro/imp	inv	inv
	pro			
		pro/imp	imp	inv
		pro/imp	imp	imp
		pro/imp	imp	inv

NPM: national planning ministry
RRA: provincially-based regulatory body
AMC: aquifer management committee
WUA: water-uses association

pro: promote
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TABLE 3: *Continuation.*

informal markets, however, this value is generally related to pumping costs, short-term availability and local use within agriculture. In contrast formal markets, functioning on the basis of a clearly-specified rights system, often communicate the difference in value between different uses and locations (such as public water-supply versus agricultural irrigation) and bear some relationship to water availability in the larger sense of sustainable abstraction and aquifer storage.

Neither form of water market, however, reflects the in-situ value associated with groundwater or the third-party costs resulting from its exploitation. Informal water markets often exacerbate overexploitation, since well owners pump as much water as they can in order to maximise returns from water sales. In contrast, markets based on volumetric rights systems can cap abstraction at sustainable levels and assist in allocating shares in the resource between categories of extractive use.

YEMEN

The water resource situation in the Yemen is extremely serious with many aquifers heavily overdrafted. The situation in the area around Taiz, the third largest city, is illustrative of growing competitive pressures between the rural and urban communities. The government is desperately seeking to improve the municipal water-supply, which is extremely erratic with breaks often exceeding 10 days. It first constructed a new wellfield in the Al Hima wadi (some 25 km upstream), following negotiations with a private land owner. This area was originally swampy and generated a significant baseflow which was utilised by agricultural irrigation. In the groundwater reconnaissance study, the resources were grossly overestimated and the impact on natural vegetation and existing users understated. Both have been effectively eradicated and most of the rural population now survive through rainfed subsistence agriculture and casual urban labour. Compensation, although promised, has not yet been paid. Subsequently, a proposal for a second emergency urban water-supply drilling programme at Habeer (further upstream) was strongly opposed by the local rural population, several of whom were shot and injured during protests. Nevertheless, a new urban wellfield was completed and is experiencing similar problems.

In the meantime, and in sharp contrast, local water markets have evolved. Agricultural well owners adjacent to the city sell water on a daily basis, either directly to urban users or to tanker operators who retail to consumers. This informal water market is highly structured with consumers paying different rates for water of different quality, and at least the rural population are able to increase income through water sales. However, such markets cut directly across strongly-held cultural norms on the common nature of water rights and the interpretation of some that water sale should be forbidden.

The technical, administrative and social aspects of rights definition pose a major difficulty for the introduction of satisfactory water markets in the groundwater case. Overall, while it is important to recognise the role that water markets can play as part of the institutional framework for groundwater management, it is equally important to recognise the limitations on that role.

Economic Instruments for Groundwater Management

There is an array of economic instruments for groundwater management, among which well licenses and abstraction fees are best known. However, there are a number of policy issues in other sectors which can have more pronounced impact on groundwater abstraction, but which are seldom considered as instruments of groundwater management. Among these are energy tariffs, import restrictions/duties for agricultural products, subsidies for drilling wells/buying pumps or for purchasing water-saving technology.

Groundwater abstraction charges in the form of a volumetric charge on actual abstraction (as opposed to a fee whose level is based on licensed abstraction) are not very common. In the few developing countries which have introduced groundwater abstraction charges (Jordan, Mexico, China and India), agriculture (which is by far the largest groundwater user) still pays only nominal charges. An advantage of using abstraction charges to reduce exploitation is that charges achieve the objective at minimum cost, by giving incentives to farmers to undertake water savings where they can be achieved.

If the revenue from groundwater abstraction charges go to the general government budget, there will be temptation to use the charge for fiscal purposes. It is far preferable to use this revenue to cover the administrative costs of regional water-management agencies or local water-user associations. If these entities are under the scrutiny of their constituents and act in a transparent manner, the revenues are likely to be spent efficiently and will not be an undue burden for water users. If the charges are not sufficiently high to constrain groundwater abstraction, they should be increased beyond the level necessary to cover administrative costs. Water users should, however, have a say in the use of surpluses generated from these charges. One possibility would be to subsidise the purchase of water-saving equipment.

Volumetric groundwater abstraction charges can be structured in various ways, but in reality scales are often linear. However, charges can also be progressive, with higher unit rates levied for higher levels of abstraction, similar to increasing block tariffs commonly used in urban water-supply in many developing countries. Another possibility is to levy higher charges during the dry season than wet season or higher charges for consumptive use than non-consumptive use, because in the latter case return flows are available for other uses. Such decisions should depend on local hydrogeological conditions.

In many countries it may prove difficult to monitor groundwater abstraction and to enforce abstraction charges. Most wells in rural areas in developing countries have no meters, and in those that do the meters are often broken or manipulated. To prevent this from happening, it is crucial that farmers understand the consequences of groundwater overpumping. It is equally important that they have a say in determining the objectives and instruments of groundwater management, including the level and structure of charges.

Energy prices in developing countries are widely subsidised. In remote areas (without electrification) diesel pumps are still used to pump groundwater and diesel prices may be fixed at low levels. In some countries, electricity tariffs for agricultural purposes are set at low levels, and sometimes flat-rate tariffs (independent of consumption) apply. Changing these tariffs could provide a major incentive for reducing groundwater pumping and economising on water use. However, in areas characterised by traditionally low electricity tariffs, any increase may be a highly political issue.

JORDAN

Jordan provides an important example of an arid country, with unreliable rainfall and extensive aquifer overdraft, attempting to get to grips with the management of groundwater resources. It has been decided that both demand and supply side management measures were urgently needed by:

- targeting investments on improving irrigation water-use efficiency and effecting real water savings, and not on extension of irrigated lands
- detailed groundwater basin studies as a precursor to defining management criteria and conservation zones
- imposition of constraints on issuing permits for the drilling of new waterwells and the replacement or modification of existing ones
- installation of abstraction meters (which has reached about 75% coverage)
- a public campaign of denouncement of illegal well operators.

Political difficulty has, however, been experienced in relation to groundwater abstraction charges. Although tariffs of up to US$0.35/$m^3$ have been imposed on industrial abstractors, objections have been voiced to raising agricultural water tariffs significantly from US$ 0.01/m^3, except in cases of well owners who exceed their licensed abstraction. There has also been resistance to reducing agricultural abstraction from the entirely fossil Qa Disi aquifer, for which hydrogeological and socio-economic studies have indicated a preferred strategy of reserving storage for high-value urban and industrial uses.

Import restrictions (such as bans or quotas) and import duties on agricultural products can keep the national price of these products above world market level. High domestic prices for agricultural products or subsidised agricultural credits are strong incentives to increase production (Myers & Kent, 1998), often at the expense of groundwater resources. Nevertheless, the trend toward gradual import liberalisation and credit cost-recovery can be expected to continue and agricultural production will tend to shift from water-scarce areas to areas with irrigation from more abundant water resources.

SOME OTHER IMPORTANT ISSUES

Planned Mining of Groundwater Storage

It should be pointed out that there is no fundamental reason while overdraft of aquifer storage is an undesirable process. If the practice of mining of groundwater reserves is carried out on a carefully-planned basis it can form part of a logical water resources management strategy. For this to be the case, however, the groundwater system under consideration should be sufficiently well investigated and understood to evaluate reliably the following:

- the rate of groundwater mining that can be achieved for the period in question
- the scale of any internal effects on the aquifer system and external impacts on the environment
- the level of interference with all existing, and potential future, groundwater users
- the economic valuation of benefits of groundwater mining for the proposed use, compared to those of alternative and future uses.

It is strongly recommended that an evaluation of these criteria are undertaken as part of a systematic analysis of water resource management options, before a conscious decision to mine groundwater storage is made. All too often, however, this is not the case and a sequence of progressive overdraft of aquifer storage is embarked upon in an anarchical or unplanned fashion, with negative long-term consequences for all groundwater users. This is more especially the case in aquifers in which some limited current recharge is occurring than for aquifers containing essentially 'fossil' storage.

Special Concerns at the Rural-Urban Interface

In many senses the rural-urban interface is often characterised by some of the greatest groundwater resource anomalies and conflicts (Foster et al, 1998; Foster et al, 1999). It is widely the area with:

- the steepest hydraulic gradient (as a result of excessive groundwater pumping in the periurban environment for municipal and industrial water-supply)
- the steepest hedonic gradient (as a result of variations in groundwater abstraction charges and end-user values between the urban and rural environment)
- the heaviest subsurface contaminant load and greatest risk of groundwater pollution (as a result of periurban industrial development and agricultural intensification in horticulture to meet urban demands).

Three issues most impact upon the status of groundwater resources and/or the rural community themselves:

- competition for available groundwater resources between urban and rural users, resulting from the pressure to transfer water-supplies to neighbouring urban areas
- potential constraints imposed on the agricultural community by policies aimed at protecting potable groundwater quality in the vicinity of municipal wellfields

- the potential impact on potable groundwater quality of the reuse of urban wastewater for agricultural irrigation.

Many regimes of land and water resource administration permit municipal water utilities/companies to explore for and develop new groundwater supplies well beyond current urban limits in contiguous agricultural areas. In some instances the impact of major wellfield development for the rural community can include:

- increased pumping head and energy costs for irrigation wells, or even the need to reset/redimension/replace pumping plant and to deepen boreholes
- increased rates of aquifer overdraft in situations of resource scarcity, compromising further the long-term sustainability of groundwater resources.

In other situations the increased pressure on groundwater resources will come from private abstractors providing urban services, including the provision of tankered water-supplies.

The situation is frequently further complicated by inadequate characterisation of the local groundwater system and misconceptions about the degree of hydraulic independence between deeper aquifers under exploitation for urban and industrial supplies and shallower aquifers providing the water-supply for agricultural irrigation. Moreover, there is no acceptance of the need to pay compensation for interference with pre-existing water rights nor existence of a transparent system by which such compensation should be estimated. On the other side, there is often a long history of not levying any realistic charge for groundwater exploitation for irrigation, leading to an entrenched situation as regards the undervaluation of groundwater resources and consequently their inefficient use in agriculture.

Another potential dimension of the urban-rural groundwater resource conflict is the pressure that may arise for land-use controls in the vicinity of urban wellfields. Controls over the application of agricultural fertilisers, pesticides, and/or slurries or on livestock grazing densities may be sought to protect the potability of the groundwater supply. Where the latter involves actual land purchase by the municipal water company, an element of compensation to individuals in the agricultural sector is implicit. However, if not, the possibility of compensation being paid to the affected farmers arises.

Where cities have significant cover of main sewerage, substantial volumes of wastewater are continuously discharged close to the downstream urban-rural interface. This wastewater represents both an important water resource (the only one worldwide which is growing in volume and availability) and also a potential public health hazard. In climates which have an extended dry season or are generally arid, urban wastewater often provides the bulk of downstream riverflow below major conurbations for many months in the year and is likely to be used for irrigation of agricultural crops on alluvial tracts. Indeed, some urban water utilities offer partially-treated wastewater and finance for improvements in irrigation technology to farmers in exchange for groundwater abstraction rights. The degree of groundwater pollution hazard involved varies widely with the aquifer pollution vulnerability and the characteristics of the wastewater (especially its salinity and content of toxic organic chemicals and heavy metals). Thus, while wastewater reuse is much needed at the urban-rural interface and around major conurbations, wherever it is practised there is a need for careful planning, operational control and systematic monitoring, albeit that, at present, it rarely receives it.

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