Chapter 2
Groundwater degradation and the limits of hydrological information

The hard evidence required to assess global trends in groundwater depletion and aquifer degradation does not exist. A recent groundwater and food security study by FAO (2003) confirms that it is not possible to assess the extent to which global food production could be at risk from overabstraction. Indeed, the search for reliable groundwater-level and abstraction data (to determine depletion rates) was fraught with problems of coverage, consistency and reliability. The study concluded that it was not possible to obtain reliable time-series data on groundwater levels in specific aquifers in India and China in order to confirm or refute assertions about the threats to food production posed by groundwater depletion.

As a report by the Ministry of Water Resources (MWR) on a water strategy for the 3-H plain in northern China notes: "*Effective management (of groundwater) is highly dependent on appropriate reliable and up-to-date information. Currently there are thousands of local and personal databases storing key technical and licensing data in a very unsatisfactory manner. An absolutely fundamental need for effective groundwater management and protection is a comprehensive, publicly accessible, groundwater database (GDB). The complete lack of a GDB is seriously constraining the formulation and implementation of effective groundwater management throughout China. The inability to access information, which at times is part of institutional secrecy, encourages inaction or incorrect decisions. GDBs are well established in almost every country where significant groundwater is used. The lack of such a database in China is surprising.*" (MWR, 2001).

Box 1 shows that the levels of uncertainty can remain high even where considerable efforts are made to analyse and interpret raw hydrogeological data.

Drawdown externalities and the sustainability issue

The impacts of overabstraction and water-level declines have been reported widely. It is sufficient to note here that overabstraction can lead to a wide array of social, economic and environmental consequences including:

- critical changes in patterns of groundwater flow to and from adjacent aquifer systems;
- declines in stream base flows, wetlands, etc. with consequent damage to ecosystems and downstream users;
- increased pumping costs and energy usage;
- land subsidence and damage to surface infrastructure;
- reduction in access to water for drinking, irrigation and other uses, particularly for the poor;

Box 1: The significance of groundwater data and its uncertainties

The problems of compiling groundwater data and interpreting abstraction records to establish and model the status of an aquifer system are well illustrated by interim reports on the Northwestern Sahara Aquifer System (SASS/OSS, 2001). This massive system covers Algeria, Tunisia and the Libyan Arab Jamahiriya and broadly comprises two super-imposed sandstones: Continental Terminal and Continental Intercalaire. Up to 8 000 borehole records and associated abstraction data from 1950 to 2000 have been compiled and a regional groundwater model constructed. A preliminary analysis of abstraction data indicates a two to threefold increase in pumped volumes throughout the aquifer system beginning in the late 1970s, peaking in 1990 and thereafter showing stabilization or slight decline. Abstraction from the system as a whole is estimated at 80 m^3/s. In 1950, abstraction was estimated at 13 m^3/s and in 1975 had reached 25 m^3/s. The impact on the overall water balance of the system is being refined through the application of a regional hydrogeological model. However, the distribution of boreholes indicates that the generation of drawdown externalities will be very localized. At control-point observation boreholes, there has been a marked lowering of the piezometric surfaces since 1980, with total drawdowns since 1950 typically of the order of 20-40 m in the exploited aquifer blocks. However, the control on abstraction data is variable (in Tunisia abstraction yearbooks have been published since 1973). In general, the levels of uncertainty associated with the data derived from a variety of data sources from the period of record are manifold. The authors of the reports emphasize the fundamental methodological differences that need to be appreciated when dealing with hydrogeological as opposed to hydrological data; specifically piezometric (water pressure head or level) altitude corrections and methods of analysis and validation in relation to hydrogeological time-series data. For these reasons, the error terms that need to be attached to any hydrogeological observation are significantly higher than those normally associated with surface water data. Thus, even where great effort and thought go into standardizing raw hydrogeological data in preparation for modelling activities, levels of uncertainty will remain high. In this particular case, model results do show a good match with the control observation data and thus provide a broad picture of the aquifer's evolution as development has proceeded. However, the data and model results would probably be too coarse for the establishment of quantitative pumping rights in specific aquifer blocks.

Box 2: The Tripoli Statement

More than 600 participants from more than 20 countries and regional and international organizations and associations attended the International Conference on "Regional Aquifer Systems in Arid Zones – Managing Non-Renewable Resources" in Tripoli, 20-24 November 1999. The Statement of the Conference reads:

"We the Participants of the Conference recognize that:

In most arid countries the scarcity of renewable water supplies implies a serious threat to sustainable coupled and balanced socio-economic growth and environmental protection. This threat is clearly more pronounced in the less wealthy countries. In many arid countries, however, the mining of non-renewable groundwater resources could provide an opportunity and a challenge, and allow water supply sustainability within foreseeable time-frames that can be progressively modified as water related technology advances.

The Conference marks a milestone in the discussion of the emerging concept of planned groundwater mining. We the Participants consider that:

Adoption of this concept at national level could have international repercussions;

A national integrated water policy is essential with, where feasible, priority given to renewable resources, and the use of treated water, including desalinated water.

We recommend that: groundwater mining time-frames should account for both quantity and quality with criteria set for use priorities, and maximum use efficiency, particularly in agriculture; care should be exercised to minimize the detrimental impact to existing communities; consideration should be given to the creation of economical low water consuming activities. We the Participants further consider that in situ development, or development based upon transferred mined groundwater, depend upon many non-hydrogeological factors outside the scope of this Conference. Nevertheless, hydrogeological constraints need to be defined for both planners and the end users. We recommend the participation of the end users in the decision making process and the enhancement of their responsibility through water use education and public awareness. We believe that for efficient water-use, cost recovery could eventually be necessary. In recognition of the fact that: some countries share aquifer systems; international law does not provide comprehensive rules for the management of such systems as yet, and clearly groundwater mining could have implications for shared water bodies; we the Participants draw the attention of Governments and International Organizations to the need for: rules on equitable utilization of shared groundwater resources, prevention of harm to such resources and the environment, exchange of information and data. We also encourage concerned countries to enter into negotiations with a view of reaching agreements on the development, management, and protection of shared groundwater resources."

- increases in the vulnerability of agriculture (and by implication food security) and other uses to climate change or natural climatic fluctuations as the economically accessible buffer stock of groundwater declines.

The term ‘overabstraction’ should not be confused with the term ‘groundwater mining’. The latter term refers only to the depletion of a stock of non-renewable groundwater, leaving the aquifer dewatered indefinitely. The planned mining of an aquifer is a strategic management option if the full physical, social and economic implications are understood and accounted for over time. The bulk of the exploited groundwater in the world’s principle stratiform aquifers was emplaced during the last 100 000 years. This applies equally to the coastal aquifers of Europe (Edmunds and Milne, 2001) as it does to the aquifers underlying the arid regions of the world where current recharge is nil or minimal. It is perhaps in the arid zones that most attention has been focused and the ‘Tripoli Statement’ echoes the concern for aquifers in arid regions (Box 2). A case in point is the current exploitation of the Nubian Sandstone Aquifer System (NSAS), which it is estimated represents 0.01 percent of the estimated total recoverable freshwater volume stored in the NSAS (Box 3).

However, even when recharge is taking place, replenishment by downward percolation of meteoric water shows high interannual variability and is a complex physical process that is difficult to evaluate (Lerner, 1990; Simmers *et al.*, 1992). Therefore, even in actively recharging systems, overabstraction should not be defined in terms of an annual balance of recharge and abstraction. Rather, it needs to be evaluated on an interannual basis since the limit between the non-renewable stock and the stock that is replenished by contemporary recharge from surface percolation is usually unknown. However, what is of real importance to decision-makers and well users is the overall reliability and productivity of a well (in terms of water levels, volumes and water quality) during a given time period. Therefore, if a well taps a particular aquifer, what is its sustainable rate of exploitation given variable periods of recharge and drought? The answer to this question is not trivial, and it requires a certain level of precision in understanding the dynamics of the physical system. Therefore, in practice, the only real management indicator for a community of groundwater users is the maximum admissible drawdown they are prepared to accept.

Yemen presents dramatic evidence of the consequences of overabstraction. According to the recent Water Resource Assessment of Yemen (WRAY-35, 1995): “*…almost all important groundwater systems in Yemen are being overexploited at alarming rates…. Worst-case predictions made in 1985 on possible depletion of the Wajid sandstone aquifer of the Sadha Plain… have unfortunately come true and groundwater levels have declined on average some 40 metres in only nine years*.” High-quality water available in shallow aquifers near Sana’a, Yemen’s capital, is expected to be depleted within a few years. This contrasts with rising water levels due to sewage infiltration under the city itself.

The scale and rate of groundwater abstraction are related directly to the massive expansion in pumping capacity that has occurred over the past five decades in many parts of the world. The number of diesel and electrical pumps in India has risen from 87 000 in 1950 to 12.58 million in 1990 (CGWB, 1995) and to an estimated 20 million today.

The impacts of long-term abstraction are readily apparent in regions where spring and seepage zones disappear or where users have to dig or drill deeper to chase a locally falling phreatic or piezometric head. In addition, the aquifer systems themselves are vulnerable to abstraction in many complex and often not immediately apparent ways. As in most discussions concerning groundwater overabstraction, these statistics focus on rates of water-level decline and the degree

BOX 3: THE NUBIAN SANDSTONE AQUIFER SYSTEM

Background

The Nubian Sandstone Aquifer System (NSAS) consists of a number of aquifers laterally and/or vertically interconnected, extending over more than 2 000 000 km^2 in the east of the Libyan Arab Jamahiriya, Egypt, northeast Chad and north Sudan. The main components of the NSAS include:

- Palaeozoic continental deposits (mainly sandstone);
- Mesozoic continental deposits, pre-Upper Cenomanian (Nubian sandstone sensu stricto);
- Post-Eocene continental deposits (mainly sandstone) in the Libyan Arab Jamahiriya, equivalent to carbonate rocks aquifer in Egypt (this component communicates with the underlying Mesozoic or Palaeozoic aquifers through Mesozoic-Cenozoic low-permeability formations).

The Nubian aquifers including the Palaeozoic and Mesozoic deposits older than the Pre-Upper Cenomanian extend over the whole Nubian Basin, although becoming very saline in the northern part. The Nubian deposits are outcropping or subcropping in all that part of the basin located south of the 26th parallel, in which the aquifer system is under unconfined condition. The unconfined part of the Nubian aquifers includes the most important groundwater potential of the whole basin. The extension of the cones of depression resulting from the water abstraction in existing and planned well fields in that part of the Nubian domain is always limited and makes it possible to multiply the centres of extraction.

The Post-Nubian aquifer, corresponding to the Post-Eocene deposits, occurs only in Egypt and the Libyan Arab Jamahiriya. It is more important in the Libyan Arab Jamahiriya in term of development potential.

The aquifer systems are not in equilibrium. The observed groundwater flow from south to north and the present natural outflow in the large and deep evaporative areas between Ajdabyia and Cairo are not due to present recharge but to paleo-recharge gradients established during pluvial periods of the late Quaternary.

Water resources and beneficial uses thereof

Data collected in the framework of the programme funded by the International Fund for Agricultural Development (IFAD) on the NSAS made it possible to estimate the amount of freshwater stored in the two aquifer systems. Following the results of this study, it is possible to envisage diverse scenarios considering different options for the development of water resources. The following table presents the main results of this freshwater resources assessment:

Country	Nubian system (Palaeozoic and Mesozoic sandstone aquifers)		Post-Nubian system (Miocene aquifers)		Total freshwater in storage[1]	Total recoverable groundwater[2]	Present extraction from systems		
	Area (km^2)	Freshwater storage (km^3)	Area (km^2)	Freshwater storage (km^3)	(km^3)	(km^3)	Post-Nubian (km^3)	Nubian (km^3)	Total (km^3)
Egypt	815 670	154 720	426 480	97 490	252 210	5 180	0.306	0.200	0.506
Libya	754 088	136 550	494 040	71 730	208 280	5 920	0.264	0.567	0.831
Chad	232 980	47 810	n.a.	n.a.	47 810	1 630	n.a.	0.000	0.000
Sudan	373 100	33 880	n.a.	n.a.	33 880	2 610	n.a.	0.840[3]	0.833
Total	2 175 838	372 960	920 520	169 220	542 180	15 340	0.570	1.607	2.170

1 Assuming a storativity of 10^{-4} for the confined part of the aquifers and 7% effective porosity for the unconfined part.
2 Assuming a maximum allowed water level decline of 100 m in the unconfined aquifer areas and 200 m in the confined aquifer areas.
3 Most extracted in the Nile Nubian Basin (833 Mm^3/year) which is not considered to be part of the Nubian Basin.

Source: CEDARE/IFAD Programme for the development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System.

Most of the water extracted from the NSAS is used for agriculture, either for large development projects in the Libyan Arab Jamahiriya or for private farms located in traditional oases in Egypt (New Valley). However, an important project designed for transporting water to the coast from the NSAS is under development in the Libyan Arab Jamahiriya. The project is already supplying some 70 Mm^3/year of water to Benghazi and to the major coastal cities west of Ajdabyia. From the above figures, it appears that the present extraction represents only 0.01 percent of the estimated total recoverable freshwater volume stored in the NSAS.

Significant issues concerning the NSAS

The large groundwater development projects planned in southern Egypt and the Libyan Arab Jamahiriya within the Nubian Basin are not expected to induce any significant effect beyond the common border between the two countries. The different options of water resources development can influence the amplitude of the cone of depression, such as the one that may be extended beyond the Egyptian-Sudanese border over some 50-70 km,

> which could be expected to be generated if particularly intensive water extraction were realized in southwest Egypt. In the north, the groundwater development at Siwa oasis from the deep aquifer (Nubian) is close to the freshwater-saltwater interface. Increasing the present abstraction may draw saline water into the freshwater aquifer. The development of a well field in the Jaghbub area, located in the Libyan Arab Jamahiriya in a symmetric position to Siwa with respect to the border line, would probably augment the risk of deterioration of the water quality in the Nubian aquifer.
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> An IFAD-funded project (for the development of a regional strategy for the utilization of the NSAS, operated by CEDARE) is assessing the regional implications of various groundwater development scenarios based on the NSAS. It will propose consultation mechanisms for the joint management of the water resources including systematic data exchange on groundwater extraction and on water-level and water-quality fluctuations.

to which extraction estimates exceed replenishment estimates. The provenance of the replenishment, whether recharge from the surface or leakage from adjacent aquifers is rarely known with any precision. However, sustainability is defined implicitly as a level at which draft and recharge are balanced (the ‘sustainable yield’ of an aquifer). This assumes that a steady state can be achieved in which water levels are stabilized. This narrow focus is often misleading. Pumping will induce water-level declines regardless of whether or not the ‘sustainable yield’ of an aquifer has been exceeded. These initial water-level declines can have major social, economic and environmental impacts long before sustainability of the groundwater resource base is threatened in any quantitative sense.

Discussions of groundwater sustainability need to focus on the ability of the resource to produce key services (including environmental services) and on the economic costs and impacts on equitable access that the loss of such services would entail. For example, declining water levels generally have large equity impacts particularly in the developing world. Wells established for drinking supply often go dry, forcing women and children to walk long distances or wait in line to obtain water to meet domestic needs. Less wealthy farmers are often only able to afford shallow, low-capacity wells. As water levels drop, they can be excluded progressively from access to groundwater by the costs of well deepening and new equipment. This effect undermines the food security and economic development benefits generated by access to groundwater. Water-level declines increase considerably the probability of environmental impacts on streams, wetlands and the occurrence of subsidence. They also increase the probability that low-quality water and pollutants will migrate into key freshwater aquifers. Finally, water-level declines can lead to economic exhaustion of the replenishable groundwater resources. As levels decline, drilling and pumping costs increase. Water may still be physically available, but the cost of extraction can be sufficiently high to exclude all but the highest-return applications. The case of the Gangetic Basin in India and Bangladesh illustrates many of these issues (Box 4).

As the example on the Gangetic Basin (Box 4) illustrates, overdraft and water-level declines typically affect the sustainability of uses that are dependent on groundwater long before the replenishable resource base is threatened with physical exhaustion. Therefore, the sustainability of socio-economic activities in relation to falling groundwater levels is complex. Any analysis of this particular issue needs to examine carefully a range of consequences, including:

- Protection of drinking-water supply sources (both access and quality).
- Equity in access and allocation and poverty alleviation.
- Maintenance of environmental values dependent on groundwater levels or groundwater discharge to watercourses.
- Food security and agricultural production.
- Economic development.

Box 4: Groundwater development in the Gangetic Basin

The Gangetic Basin is filled with unconsolidated alluvial materials to a depth of about 6 000 m and receives an average of 1 500 mm of rainfall each year (Rogers, Lydon *et al.*, 1989). The total amount of groundwater in storage would be sufficient to meet all needs for centuries with little danger of physical depletion.

Despite the large stock of water in storage, groundwater development is having major impacts. In Bangladesh, water-level fluctuations are causing shallow wells to go dry, particularly during summer. This creates major difficulties for villagers in obtaining drinking-water supplies (Sadeque, 1996). It also has major equity effects. Wealthy farmers can afford to deepen existing wells or install new ones; those who are less wealthy often cannot afford the cost of chasing the water table. Environmental impacts could also be major. Kahnert and Levine (1989) commented in their summary of a symposium on groundwater irrigation and the rural poor that: “the data show significant seasonal variations in both the water table and the flow of the Ganges in its lower reaches.” Participants in the symposium also expressed concern about the potential impact of increased groundwater extractions on the base flow into the Ganges River at low flow periods. Modelling activities currently underway appear to substantiate these concerns. Results suggest that dry season flows at Farakha Barrage near the Bangladesh border could decline by about 75 percent if historical groundwater development patterns continue (Ilich, 1996).

Declines in dry season flow are a point of contention between India and Bangladesh. For Bangladesh, these flows are critical for irrigation, drinking-water supply and for sustaining mangrove areas along the coast. Furthermore, in Bangladesh, 70-80 percent of total animal protein consumption is dependent on fish. Activities affecting floods and drainage could interrupt approximately 60 percent of the nation’s fish production (Rogers, Lydon *et al.*, 1989).

Finally, declining water tables have major implications for energy consumption. India’s electricity deficit now runs at 19 percent for base load and at more than 30 percent for peak load. Much of the problem relates to agricultural use, primarily pumping for irrigation. In many states, official figures published by the state electricity boards indicate that agricultural demand exceeds 40 percent of consumption. In some, such as Haryana, it exceeds 50 percent. While these figures may be misleading (they include massive ‘non-technical’ losses), the rate of growth in agricultural electricity consumption has been dramatic. Power for groundwater pumping is highly subsidized. Farmers usually pay a flat rate based on pump horsepower. As a result, when water tables fall, farmers have little incentive to reduce extraction. This exacerbates both energy and overdraft-related problems.

Groundwater extraction and migration of low-quality water

Vulnerability to declines in groundwater quality as a result of increased groundwater extraction is particularly high in certain contexts. These include:

- Coastal zones: Intrusion of saline ocean water is a common result of pumping, particularly in locations where sediments are highly permeable and in small islands and atolls.
- Interbedded high- and low-quality aquifers: In many locations, aquifers containing high- and low-quality water are interlayered.
- Locations where low-quality water is present on the surface or in adjacent rock formations. Pumping often causes lateral migration of low-quality water from adjacent aquifers.
- Locations where rock formations encourage rapid flow. Water flows much more rapidly through karstic limestone or other rock formations where large interconnected fractures or cavities are present. These locations tend to be much more vulnerable to rapid contamination from chemical and bacterial sources.
- Locations where the geochemistry of adjacent waters and/or the geological formations is incompatible. Groundwater geochemistry often differs. This can result in a wide variety of chemical reactions when water containing different levels of key constituents or having differing pH or redox potentials is drawn into and mixes with water in pumped aquifers.

Several of the above characteristics are often present at a single location. However, beyond the vulnerability of different regions, it is important to recognize that quality deterioration is an unavoidable result of use.

The impact of quality declines on the sustainability of uses that are dependent on groundwater can equal or exceed the direct impact of groundwater overdraft. Quality declines can reduce and destroy the value of entire aquifers as a source of water. To this extent, quality declines associated with increased groundwater extraction can have as major an impact on the sustainability of key uses as more publicized problems such as groundwater overdraft.

RISING WATER LEVELS AND WATERLOGGING

Waterlogging induced by irrigation

Pakistan and India contain some of the most extensively documented cases of irrigation-induced waterlogging and salinization. However, even here, it is difficult to evaluate the extent of problems based on available figures. In India, the Ministry of Agriculture estimated that the total area affected by waterlogging as a result of both groundwater rises and poorly controlled irrigation was 8.5 million ha in 1990 (Vaidyanathan, 1994). In contrast, estimates made by the Central Water Commission for 1990, which considered only areas affected by groundwater rises, totalled 1.6 million ha (Vaidyanathan, 1994). Regardless of the actual extent, waterlogging problems represent a major surface water and groundwater management challenge. This challenge cannot be addressed in the absence of an integrated approach that incorporates surface-water imports and use as well as groundwater. Large areas in Pakistan face similar problems. Rising water levels in the command of surface irrigation systems have fundamental implications for the sustainability of social objectives that are groundwater dependent. In the case of food security, estimates indicate that irrigation-induced salinity and waterlogging reduce crop yields in Pakistan and Egypt by 30 percent (FAO, 1997). In India, the problem is serious enough to threaten the growth of the agricultural economy (Joshi *et al.*, 1995). The impact of waterlogging and salinization on farmers and regional economies can be insidious. In the initial years, the introduction of irrigation often causes a dynamic transformation of regional and household economies. Farmers introduce high-yielding varieties of grain and are able to grow valuable market crops. Wealth is created. However, as the water table rises, the ‘bubble economy’ based on unsustainable water management practices deflates. Once salinized, land and the unsaturated zone of the soil are difficult and expensive to reclaim. Ultimately, many farm families (and regional economies) may be worse off than before the introduction of irrigation unless sustainable and affordable methods of remediation are found.

Water-level rises under urban areas

Water-level rises are a major feature in many urban areas, particularly once cities begin to rely on imported supplies. Although urbanization may reduce direct infiltration of rainfall because of the large impermeable area created, recharge below cities is often far higher than pre-urban levels (Morris *et al.*, 1994; BGS, 1995). In a recent study, the increases in recharge under Merida, Hat Yai and Santa Cruz (cities in Mexico, Thailand and Bolivia, respectively) ranged from 130 to 600 percent. In Lima, Peru, recharge has increased from essentially zero to 700 mm/year (Morris *et al.*, 1994). As most of this recharge comes from leaking sewers and water mains, the potential for pollution is high. Where water imports induce rising water levels in unconfined aquifers, the effect enables shallow wells to serve as a major source of water supply for the poor. However, as pollution levels are generally much higher in shallow urban aquifers, particularly in areas not served by sewer systems, those dependent on shallow wells face major health risks. This is well illustrated by the case of Sana’a, Yemen, where water levels under the city are rising despite general conditions of overdraft in aquifers supplying the city. Furthermore,

Box 5: Groundwater management in the Indus Basin

Recent estimates are that irrigated land furnishes 90 percent by value of Pakistan's agricultural production, accounting for 26 percent of its gross domestic product (GDP) and employing 54 percent of the labour force. On the evidence of current investments, priorities in irrigated agriculture outweigh other interventions. Maintaining a bank of soil resources and flow of water resources to support food production to a population growing at 3.0 percent/year has become an imperative for Pakistan. The bulk of this productivity is associated with the Indus Basin.

The Indus Basin is filled with thick alluvial sediments deposited by the Indus River and its five main tributaries (Jhelum, Chenab, Ravi, Sutlej and Beas) forming a thick set (300-500 m) of unconfined and leaky aquifers. Before the introduction of a weir-controlled canal irrigation system, the groundwater table was relatively deep under most of the plain. As a result of the additional recharge introduced by irrigation, the water table started rising at a rate of 15-75 cm/year. The position of the water table before and after the introduction of the large canal networks in the upper part of the basin rose 20-30 m in 80-100 years. The quality of groundwater varies in vertical and horizontal directions and is related to recharge of the aquifer. In general, water from shallow wells located near sources of recharge is of good quality. Along the rivers and in the upper reaches of the doabs, where precipitation is a major source of recharge and maximum canal supply is available, groundwater usually contains less than 1 000 ppm of dissolved solids (1.56 dS/n).

The Indus Basin was developed through surface irrigation in the late nineteenth century but the threat to the system of saline accumulation in irrigated soils was appreciated by the original design engineers. The results have been:

- Public tubewell development started in the 1960s through Salinity Control and Reclamation Projects (SCARPs). Because drainage projects alone generally have a low economic rate of return, priority has been given to locating SCARPs in areas of usable-quality groundwater. As a result, 90 percent of the SCARP tubewells and 95 percent of the pumped groundwater is from freshwater groundwater zones. SCARPs have evolved into groundwater supply projects in which drainage is a by-product.
- The SCARP development has triggered the capacity of the private sector to develop good-quality groundwater (something not appreciated in the early planning stages).
- The salt balances of the Indus Basin and its associated sub-basins have been disrupted as the hydrochemical systems have become progressively closed and the supplemental generation of salt through waterlogging has further exacerbated the positive salt balance.
- The Indus Basin is effectively a saline sink with minimal flushing and outflow. This applies to the Indus Plain as much as to the North West Frontier Province (NWFP) and Baluchistan sub-basins, which are also in danger of becoming closed subsystems.
- The recently launched National Drainage Programme has dropped subsidies from public tubewells in fresh groundwater areas.

The physical and chemical environment in which groundwater is found and is evolving is complex, particularly in the shallow horizons that have experienced recent groundwater recovery and quality changes. Relatively fresh groundwater occurs side by side with saline groundwater or under or overlain with saline groundwater. This requires a high degree of operational knowledge in the management of groundwater in order to ensure its sustainability in terms of quantity and quality. Therefore, the identification of hydrogeological processes and the establishment of a physiographic framework are imperative in order to both explain and quantify the groundwater occurrences and the rate of aquifer replenishment and depletion.

high water levels under urban areas cause drainage problems, leading to the creation of stagnant and highly polluted surface water bodies.

Water-level changes in response to vegetation cover

Land-use changes can have a significant impact on groundwater levels. Forest and vegetation cover have long been recognized as major factors influencing runoff, infiltration and evapotranspiration from shallow water tables. Watershed treatment involving the establishment of tree, bush and other plant cover is widely used as a way of reducing runoff and increasing infiltration. This is frequently assumed to increase recharge and is advocated as a core part of packages to address groundwater overdraft. However, the effect of surface vegetation on groundwater levels is not automatic. It depends on the balance between improvements in infiltration caused by increased vegetation and relative changes induced in evapotranspiration. In some cases, removal of forest cover has caused water levels to rise significantly with major environmental consequences, e.g. in much of New South Wales, Australia.

POLLUTION EXTERNALITIES

Pollution is widely recognized as one of the most serious challenge to the sustainable management of groundwater resources. The significance of pollution for groundwater resources is increased by the long time scale at which processes affecting groundwater function. As Morris *et al.* (1994) comment: “It is important to appreciate the differences between surface water and groundwater systems. In the former, the water is typically being replenished, at least in the case of rivers, within time-scales of weeks or at most months. Replenishment times for groundwater systems are very much longer. This is because water usually takes many years to move through the soil and unsaturated zone of the aquifer. Once there, it can take a further period of many tens or hundreds of years to flow into a supply borehole.” In some of the deeper aquifers, groundwater is likely to be thousands of years old (Edmunds and Wright, 1979; Edmunds *et al.*, 1987). In addition to the relatively slow movement of water in many aquifers, rocks and soil absorb and otherwise attenuate the presence of pollutants. Not all aquifers are equally vulnerable to pollution. Those where fractures or cavities permit rapid flow tend to be more vulnerable than those where water flows slowly through porous media and more opportunities exist for attenuation of pollutants. However, vulnerability to pollution has an inverse relationship to the difficulty of remediation. Once polluted, slow movement of groundwater through a porous aquifer generally makes cleanup difficult, expensive, and in some cases impossible.

Beyond the inherent vulnerability of aquifers to contamination, much depends on the nature of pollutant sources. Contaminant behaviour varies greatly with respect to the specific transport properties in each aquifer system. In addition, the range of contaminant types is increasing as new products appear in effluent disposal and land application. Three main sources of groundwater pollution are: agricultural, urban and industrial.

Agricultural pollution

In many developing countries, agricultural chemical use has been low in comparison to levels in industrialized countries. This may no longer be the case, particularly in countries such as India and China where irrigation is extensive. Concerns over groundwater pollution from agricultural chemicals were raised as a major issue in India more than two decades ago (Chaturvedi, 1976) but few data were available. At that time, the level of agricultural chemical use was very low. However, by 1991, fertilizer use per hectare of agricultural land was 60 percent higher than in the United States of America (Repetto, 1994). At present, no agency in India has a systematic programme for monitoring potential non-point sources of pollution. However, fragmentary data indicating the potential extent of agricultural pollution problems are available. For example, maps prepared by the Central Ground Water Board (CGWB) show nitrate concentrations in Gujarat exceeding 45 mg/litre (the WHO’s recommended maximum for drinking-water) in more than 370 sample sites scattered across the state (Phadtare, 1998). How much of this pollution is related to agricultural pollution and how much to domestic or other sources is unknown.

Aside from non-point-source considerations, it is important to recognize that nitrate and other nutrient pollution in groundwater is often related to agricultural practices other than the use of chemical fertilizers. Any location where animal wastes are concentrated, such as feed lots or poultry farms, can release high levels of nutrients into groundwater. In addition to nutrients, pesticides and herbicides are other major sources of groundwater pollution related to agriculture. In some circumstances, soils can absorb or immobilize a large fraction of such agricultural chemicals. However, many pesticides and herbicides break down slowly under aquifer conditions or can transform into more toxic compounds. As a result, they can persist over long time periods. In any case, groundwater pollution data are generally scarce and chemical analysis of water samples needs to be specific to detect their presence.

The dispersed nature of sources of pollutants is a core challenge facing both monitoring and control of groundwater pollution related to agriculture. Unlike industry or municipal sewage systems, agricultural pollutants are dispersed over large land areas. While return flows in drainage canals can be monitored, it is difficult to determine the extent of direct seepage of pollutants through soils and into the groundwater until contaminant concentrations in groundwater become significant.

Urban groundwater pollution

The additional recharge in urban areas is derived principally from leaking sewers and other wastewater sources. Broken sewers in the United States of America are estimated to lose 950 Mm^3 of wastewater each year (Pedley and Howard, 1997). Much of this represents polluted recharge to groundwater. Direct leakage of wastewater to groundwater in developing countries is probably much higher. In many cities, a large portion of the wastewater generated is discharged directly into unlined canals. Where sewer systems exist, leakage levels are almost certainly much higher than in the United States of America because of lack of resources for maintenance, variability in construction materials and absence of adequate treatment facilities. Furthermore, in many urban and peri-urban areas, pit latrines and soak pits are used to dispose of domestic wastewater. These are often relatively deep (more than 3 m) and discharge wastes below the soil and weathered zone layers that have the greatest capacity to filter, absorb and otherwise attenuate pollutant concentrations (Pedley and Howard, 1997).

The impact of urban wastewater discharges on groundwater is well illustrated by the cases of Santa Cruz, Bolivia, and Hat Yai, Thailand. In both these cities, direct discharge of untreated wastewater has led to substantial increases in pollutants (NO_3^-, NH_4^+, Cl^-, faecal coliforms, and dissolved organic carbon) in the shallow aquifers. The quality of deeper groundwater is still good but pollution fronts are moving downward in response to extraction from deeper levels for drinking-water supply and other uses (Morris *et al.*, 1994). This situation is typical of many cities, particularly in rapidly urbanizing sections of the developing world.

Water supply officials tend to recognize the potential impact of waste discharge on chemical contamination of groundwater by nitrates and other compounds. However, it is often assumed that the filtering action of aquifers and relatively long residence times underground are sufficient to remove pathogens except where open or poorly sealed wells are contaminated directly by surface water inflows. This perception is inaccurate. According to Pedley and Howard (1997): “Bacteria can survive up to 50 days or more in subsurface environments and viruses for far longer.”

Overall, the pollution of shallow aquifers under cities represents a major threat to the sustainability of drinking-water supplies in many urban areas throughout the world (BGS, 1995; World Bank, 1998). This threat is particularly high where regional hydrogeological conditions permit rapid flow of contaminated water into aquifers and the wells tapping them. For example, aquifers in karstic carbonate rocks or fracture zones are far more susceptible to contamination than aquifers where groundwater flows through porous media such as soil or sandstone. The threat is also particularly high where large portions of the urban population both dispose of untreated wastes directly through soakaways and latrine pits and also depend on shallow wells for drinking-water supply.

Industrial pollutants

Public attention with regard to groundwater pollution often focuses on 'hot spots' where industrial activities have polluted large areas. Sites of this type often receive national attention. Jetpur, a textile town in Gujarat, India, where more than 1 200 small industrial units drain effluents containing cadmium, zinc, mercury, chromium and other pollutants into small rivers and thence into groundwater, is a prime example (Moench and Matzger, 1994). Governmental monitoring and cleanup activities also tend to focus on high-profile sites. The 'superfund' sites in the United States of America and the activities of the state and central pollution control boards in India are typical of many governmental initiatives, particularly during early phases, when the significance of groundwater pollution is only beginning to be recognized. In India, the Central Pollution Control Board has a programme to monitor groundwater quality in 22 critically polluted sites (Moench, 1996). However, there is no baseline monitoring of potential industrial pollutants except within these hot spots.

The hot-spot focus of public attention and many government initiatives tends to downplay the importance of dispersed sources of industrial pollutants such as trace metals and organic solvents. Because of their low solubility, many such pollutants have extremely long residence times in aquifers. Because they do not dissolve rapidly, they can remain indefinitely as a concentrated source of pollution within an aquifer. In some cases, gradual volatilization of organic solvents in aquifers can become an air-quality hazard. Dispersed sources of industrial pollutants are much harder to identify, monitor and control than the effluent from specific factories or industrial areas. As such, these dispersed sources may well represent a greater threat to groundwater resources than concentrated industrial effluent flows.

Data on groundwater pollution in developing countries are generally unavailable. This is particularly the case for pollution related to dispersed sources such as mining activities, underground storage tanks and direct discharge of effluent to water bodies and watercourses. However, with increases in transportation needs and industrial activities, the number of sites where pollution is occurring is increasing rapidly.

Implications of groundwater pollution

The full impacts of groundwater pollution on health, agriculture and the environment have not been assessed comprehensively. In the case of health impacts, Pedley and Howard (1997) observe that: "*The contribution made by contaminated groundwater to the global incidence of waterborne disease cannot be assessed easily; for many countries the incidence of waterborne disease is not known accurately and the data for groundwater usage are not available. Where public health statistics are available, the data are insufficient to determine the source of the water involved in the transmission of the disease.*" However, in comparison with other topics such as the environment, collection of public health data is widespread and relatively well established. The difficulty of assessing the impact of groundwater changes on health (where at least some data are available) gives an indication of the magnitude of the challenge in assessing impacts on other values.

Lack of information on the health and other costs associated with groundwater pollution and quality declines may lead to questions regarding the importance of these problems. While the dangers of pathogenic organisms are recognized, officials in developing-country situations often emphasize informally the lack of evidence that diseases, such as methoglobanemia, or responses to toxic substances are occurring in any but the most polluted areas. Based on this perception, they often advocate relaxation of standards. Part of this response may be due to the widespread incidence of many other health and disease problems, making diagnosis difficult. Part may also be because of priorities. Pollution control and aquifer remediation are expensive. In the United States of America, substantial debate has emerged over the cost of cleanup in relation to the value of groundwater resources (National Research Council, 1997). In developing countries, demands on limited financial resources are often more intensive. As a result, more questions arise regarding large investments in pollution control or aquifer remediation that have few immediately observable returns.

The above observations do not imply that the human and environmental burdens associated with groundwater pollution are minor. Diseases related to water pollution are a major concern in many parts of the world. In 1994, cholera caused more than 10 000 deaths; in recent years, 25 000 deaths have been caused by typhoid, 110 000 by amoebae; and diarrhoeal diseases have claimed the lives of 3.2 million children under 5 years old (Pedley and Howard, 1997). Comprehensive data on deaths and disease caused by absorption of trace metals and other pollutants are not available. However, overall, days lost to disease and the continuing burden of sickness on society far exceed the actual number of deaths. Although the amount of death and disease that can be attributed to groundwater pollution per se as opposed to surface water pollution is unknown, it adds a continuing burden to the health of large populations, particularly in developing countries. In a similar but mostly undocumented manner, groundwater pollution affects a wide range of other key environmental and social values.

Soil and groundwater contamination from industrial and population expansion is of widespread concern. The prevalence of contaminants at hazardous waste sites is well documented. If they are not removed or sequestered, they can contaminate millions of litres of groundwater over time scales of decades and centuries. The remediation of polluted groundwater is driven by the need to reduce risks by achieving regulatory compliance, or in reducing liabilities, at the lowest cost. The high costs and ineffectiveness of groundwater extraction methods in removing unwanted chemical constituents completely from aquifer systems has motivated the development, testing, and application of *in situ* treatment methods.