THE ROYAL SOCIETY

Groundwater: the processes and global significance of aquifer degradation

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The exploitation of groundwater resources for human use dates from the earliest civilizations, but massive resource development has been largely restricted to the past 50 years. Although global in scope, the emphasis of this paper is on groundwater-based economies in a developing nation context, where accelerated resource development has brought major social and economic benefits over the past 20 years. This results from groundwater's significant role in urban water supply and in rural livelihoods, including irrigated agriculture. However, little of the economic benefit of resource development has been reinvested in groundwater management, and concerns about aquifer degradation and resource sustainability began to arise.

A general review, for a broad-based audience, is given of the mechanisms and significance of three semi-independent facets of aquifer degradation. These are (i) depletion of aquifer storage and its effects on groundwater availability, terrestrial and aquatic ecosystems; (ii) groundwater salinization arising from various different processes of induced hydraulic disturbance and soil fractionation; and (iii) vulnerability of aquifers to pollution from land-use and effluent discharge practices related to both urban development and agricultural intensification.

Globally, data with which to assess the status of aquifer degradation are of questionable reliability, inadequate coverage and poor compilation. Recourse has to be made to 'type examples' and assumptions about the extension of similar hydrogeological settings likely to be experiencing similar conditions of groundwater demand and subsurface contaminant load. It is concluded that (i) aquifer degradation is much more than a localized problem because the sustainability of the resource base for much of the rapid socio-economic development of the second half of the twentieth century is threatened on quite a widespread geographical basis; and (ii) major (and long overdue) investments in groundwater resource and quality protection are urgently needed. These investments include appropriate institutional provisions, demand-side management, supply-side enhancement and pollution control.

Keywords: groundwater; aquifer degradation; resource depletion; groundwater pollution; resource protection

1. GROUNDWATER: SIGNIFICANCE FOR HUMAN DEVELOPMENT

(a) *The subterranean source of civilization*

Since earliest antiquity humankind has obtained much of its basic requirement for good quality water from subterranean sources. Springs, the surface manifestation of underground water, have played a fundamental role in human settlement and social development. But for many millennia, capability to abstract groundwater was tiny compared with the available resource.

Heavy exploitation followed major advances in geological knowledge, well drilling, pump technology and rural electrification, which for most regions dated from the 1950s (Foster *et al.* 2000). Today, with an estimated total global withdrawal of 600–700 $km^3\ yr^{-1}$ (Zektser & Margat 2003), in one sense groundwater is the world's most extracted raw material: and, for example, forms a cornerstone of the Asian 'green agricultural revolution', provides *ca.* 70% of piped water supply in the European Union and supports rural livelihoods across extensive areas of sub-Saharan Africa.

(b) *A vast reservoir of freshwater*

Groundwater systems (aquifers with in some cases interbedded aquitards) unquestionably constitute the predominant reservoir and strategic reserve of freshwater storage on Earth: probably *ca.* 30% of the global total and as much as 98% if that bound up in the polar ice caps and glaciers is discounted (Shiklomanov 1998). Certain aquifers (such as the examples shown in figure 1) extend quite uniformly over very large land areas and have much more storage than all of the world's surface reservoirs and lakes. In sharp contrast to surface water bodies, they lose very little of their stored water by direct evaporation.

However, calculation of the huge total volume of global groundwater storage is by no means straightforward, and the precision and usefulness of any calculation will inevitably be open to question. Estimates range from 7 000 000 km^3 (Nace 1971) to 23 400 000 km^3 (Korzun

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One contribution of 11 to a Theme Issue 'Freshwater and welfare fragility: syndromes, vulnerabilities and challenges'.

DOI 10.1098/rstb.2003.1380

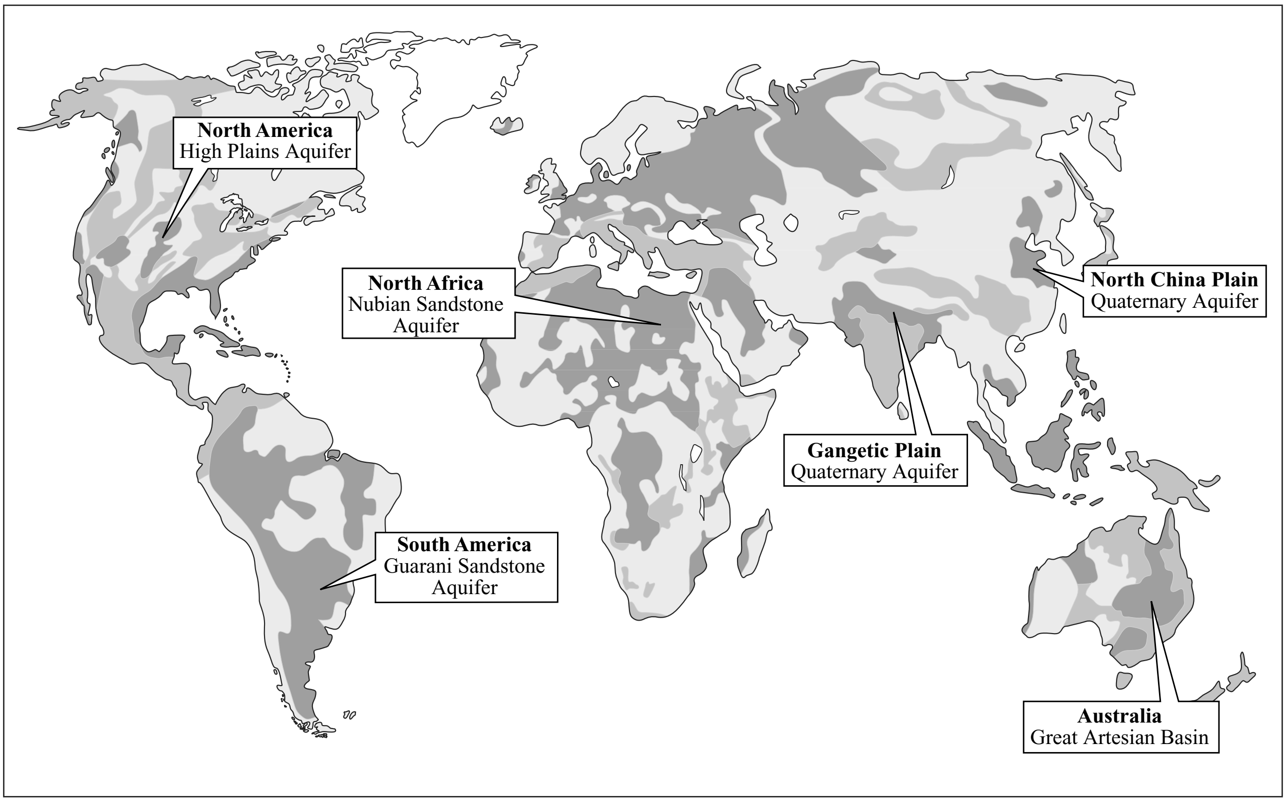


Figure 1. Simplified hydrogeological map of the world. This preliminary map is based on data from a joint UNESCO–International Association of Hydrogeologists project, and is reproduced with their permission; it shows both the widespread occurrence of geological formations containing useful groundwater and the location of some of the world's largest aquifers which have vast storage reserves in part of palaeo-groundwater. Dark grey areas, major regional aquifer systems; mid-grey areas, areas with some important but complex aquifers; light grey areas, areas of generally low permeability with local minor aquifers.

1974): but all are subject to major assumptions about the effective depth and effective porosity of the freshwater zone.

(c) *Hydrogeological diversity of aquifer types*

Whereas all aquifers have two fundamental characteristics—a capacity for groundwater storage and a capacity for groundwater flow—different geological formations vary widely in the degree to which they possess these properties (figure 2). Moreover, their areal extent can vary with geological structure from a few square kilometres to many thousands of square kilometres (figure 1). The most significant elements of the hydrogeological diversity of aquifer types are

(i) major variation of aquifer unit storage capacity (storativity) between unconsolidated granular sediments and highly consolidated fractured rocks, and
(ii) wide variation in aquifer saturated thickness between different depositional types, resulting in a wide range of groundwater flow potential (transmissivity).

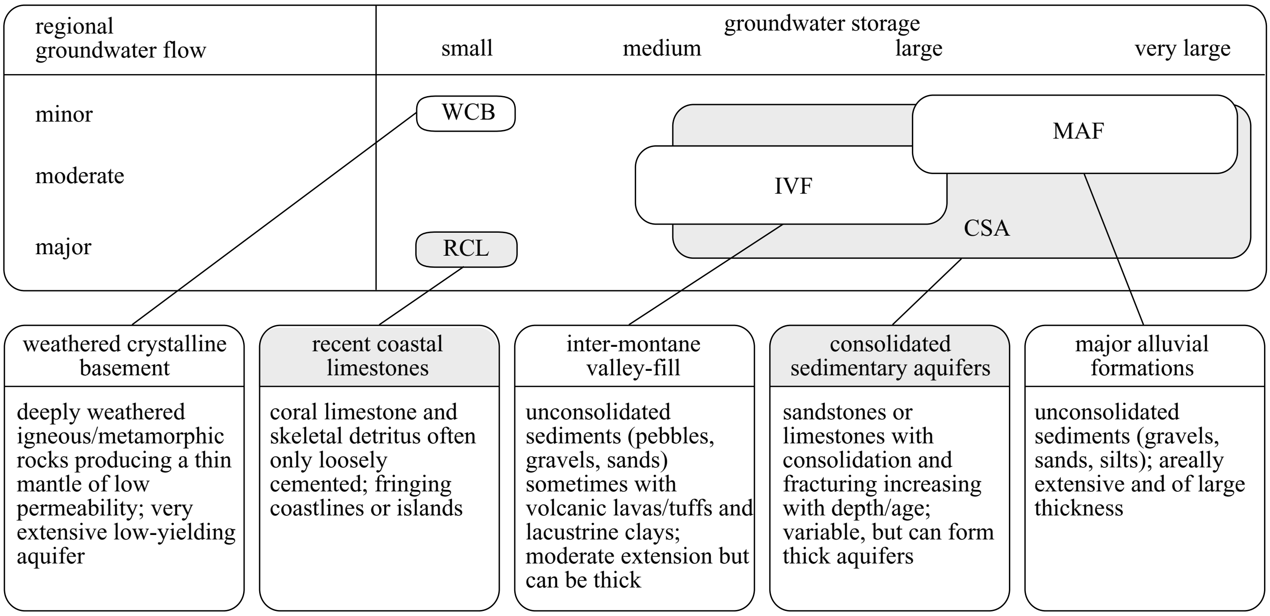
This paper focuses primarily on the so-called major aquifers, which possess large storage reserves and provide high well yields, but extensive minor aquifers also play a critical role in meeting human needs from water supply (Chilton & Foster 1995).

(d) *The boom in groundwater resource exploitation*

Rapid expansion in groundwater exploitation occurred during 1950–1975 in many industrialized nations and during 1970–1990 in most parts of the developing world. Comprehensive statistics on abstraction and use are not available, but globally groundwater is estimated (Zektser & Margat 2003) to provide at least 50% of current potable water supplies; 40% of the demand from those industries that do not use mains water, and 20% for water use in irrigated agriculture. These proportions, however, vary widely from country to country and within countries. Moreover, the value of groundwater to society should not be gauged solely in terms of relative volumetric abstraction. Compared with surface water, groundwater use often brings large economic benefits per unit volume, because of ready local availability, high drought reliability and generally good quality requiring minimal treatment (Burke & Moench 2000).

The dependence of expanding cities and innumerable medium-sized towns on groundwater is intensifying (Foster *et al.* 1997), such that it is believed some 1500 million urban dwellers worldwide depend on well, borehole and spring sources. In many instances urban society also relies upon underlying aquifers to dispose of its wastes.

The contribution of groundwater to irrigated agriculture is, in part, of very high productivity in terms of crop yield



weathered crystalline basement: deeply weathered igneous/metamorphic rocks producing a thin mantle of low permeability; very extensive low-yielding aquifer

recent coastal limestones: coral limestone and skeletal detritus often only loosely cemented; fringing coastlines or islands

inter-montane valley-fill: unconsolidated sediments (pebbles, gravels, sands) sometimes with volcanic lavas/tuffs and lacustrine clays; moderate extension but can be thick

consolidated sedimentary aquifers: sandstones or limestones with consolidation and fracturing increasing with depth/age; variable, but can form thick aquifers

major alluvial formations: unconsolidated sediments (gravels, sands, silts); areally extensive and of large thickness

Figure 2. Summary of key properties of the most widely occurring aquifer types. The very wide diversity of aquifer types (in terms of storage and flow characteristics) is shown in a qualitative way and related to their geological origin.

Table 1. Groundwater use for agricultural irrigation in selected nations.
(These data extracted from the files of the UN Food and Agriculture Organization Aquastat Database system correspond to country returns sometime during the period 1990–1997; although the best available they are of somewhat variable quality and questionable accuracy and also do not distinguish supplementary from near-continuous irrigation nor identify conjunctive use of groundwater and surface water.)

country	irrigated area (km^2)	irrigation use (km^3 yr^{-1})	proportion of groundwater (%)
India	501 000	460	53
China	480 000	408	18
Pakistan	143 000	151	34
Iran	73 000	64	50
Mexico	54 000	61	27
Bangladesh	38 000	13	69
Argentina	16 000	19	25
Morocco	11 000	10	31

and value (Llamas & Custodio 2002). Selected country-level data are shown in table 1, and groundwater is believed overall to represent approaching 30% of the total irrigation supply. This use is, of course, relatively tolerant of many components of groundwater quality with the important exception of salinity.

The case of India (table 1) is worthy of specific mention. Groundwater supplies directly *ca.* 80% of domestic water supply in rural areas, with some 2.8–3.0 million hand-pump boreholes having been constructed over the past 30 years (Nigam *et al.* 1998). Further, some 244 km^3 yr^{-1} are currently estimated to be pumped for irrigation from *ca.* 15–17 million dugwells and tubewells equipped with motorized pumps, with as much as 70% of national agricultural production being supported by groundwater (Burke & Moench 2000).

2. GROUNDWATER USE: THE QUESTION OF SUSTAINABILITY

The rapid, and largely uncontrolled, expansion in groundwater exploitation generated major social and economic benefits, but more recently it is also encountering significant problems (table 2). In some cases current abstraction rates are not physically sustainable in the longer term (figure 3), and in numerous others there have been varying degrees of aquifer degradation or environmental impact or both (Morris *et al.* 2003).

Most consumptive use of pumped groundwater is by irrigated agriculture, but there is also heavy urban water-supply abstraction, both for public and private supply, coupled with inadequate attention to disposal and/or re-use of the wastewater generated. In the following part of the paper the processes of, and limitations on, aquifer replenishment are first introduced, and then the externalities of groundwater development, together with the physical and economic consequences of overdraft (mining) of aquifer storage reserves, are discussed.

(a) *Aquifer replenishment: processes, limitations and uncertainties*

Groundwater is in slow motion from areas of aquifer recharge (which favour the infiltration of excess rainfall

Table 2. Benefits and problems of groundwater development.
(Individual socio-economic benefits are in no sense directly correlated with specific sustainability problems, and the latter do not occur in all aquifers and in all areas.)

socio-economic benefits	resource sustainability problems
economical provision of good quality urban water supplies low-cost development of drought-reliable rural water supplies accessible and reliable water supply for irrigated crop cultivation improved drainage and salinity alleviation in some areas	inefficient resource use on a very widespread basis growing social inequity in access to groundwater physically unsustainable abstraction rates in more arid regions localized land subsidence due to aquitard compaction irreversible aquifer damage locally due to saline intrusion/upconing damage to some groundwater-dependent ecosystems reduction in dry-weather baseflow in some downstream watercourses serious natural quality hazards encountered in some aquifers (Edmunds & Smedley 1996)

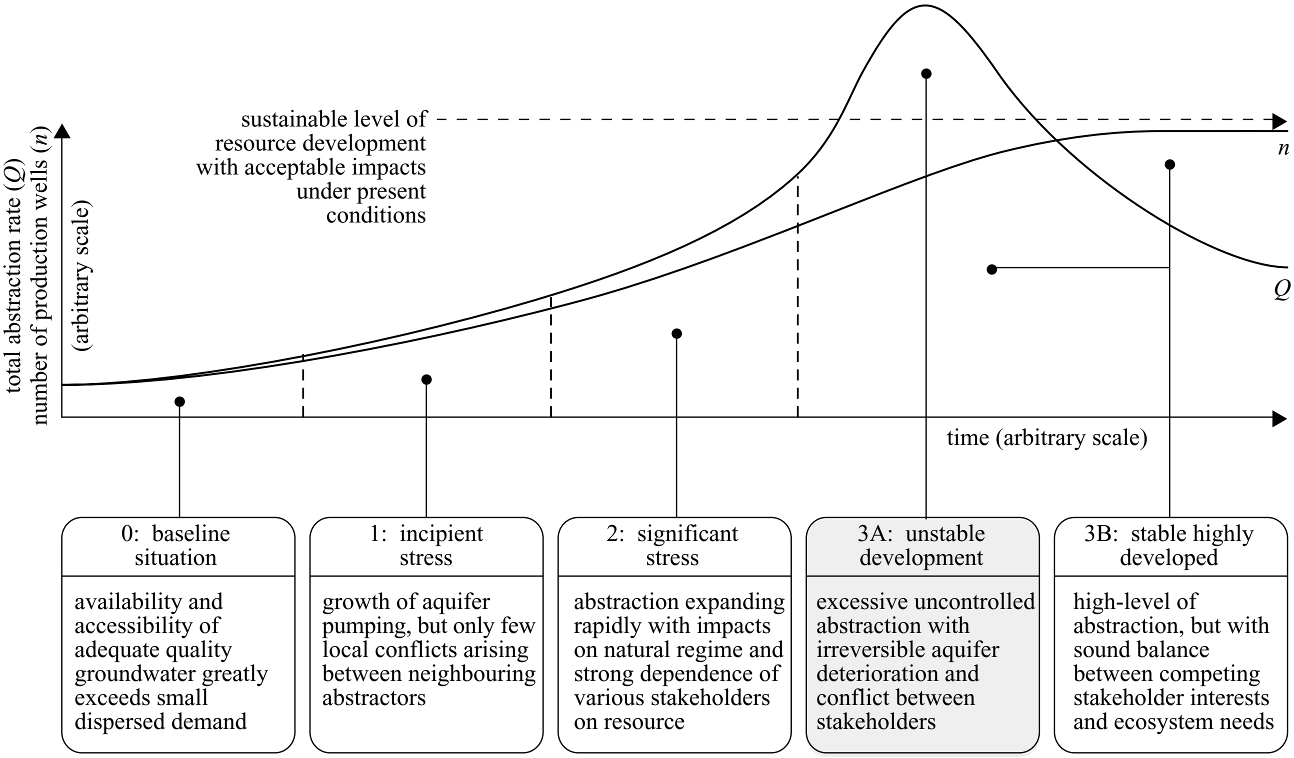


Figure 3. Stages of groundwater resource development in a major aquifer and their corresponding management needs. If the condition of unstable development arises it is likely to result in a loss of potential yield even after balance is achieved as a result of aquifer degradation; the illustration does not include consideration of downstream dependencies on aquifer discharge nor of temporal variations in aquifer recharge rates which can arise as a result of a range of independent causes.

and/or surface run-off) to areas of aquifer discharge (as springs and seepages to watercourses, wetlands and coastal zones). The large storage of many aquifers helps to buffer inputs, and transforms highly variable recharge regimes into much more constant discharge regimes, and means that groundwater residence times are often counted in decades, centuries or even millennia (figure 4). It is important to distinguish between shallow groundwater linked directly to modern recharge processes (Simmers *et al.* 1997) and groundwater in deeper (generally more confined) aquifers, most of which may have been recharged at earlier wetter periods of Quaternary history.

The estimation of contemporary aquifer recharge rates to shallow aquifers is of fundamental significance when considering the sustainability of groundwater resource development. Furthermore, understanding aquifer recharge mechanisms and their linkages with land use is needed for the catchment-scale evaluations of resources, which are an essential basis for integrated water resources management.

The common paradigm of ‘constant average rates of present-day aquifer recharge’ is false and can lead to serious ‘double resource accounting’, especially in the more arid regions. In reality the contemporary rate of aquifer recharge varies considerably with the following (Foster *et al.* 2000).

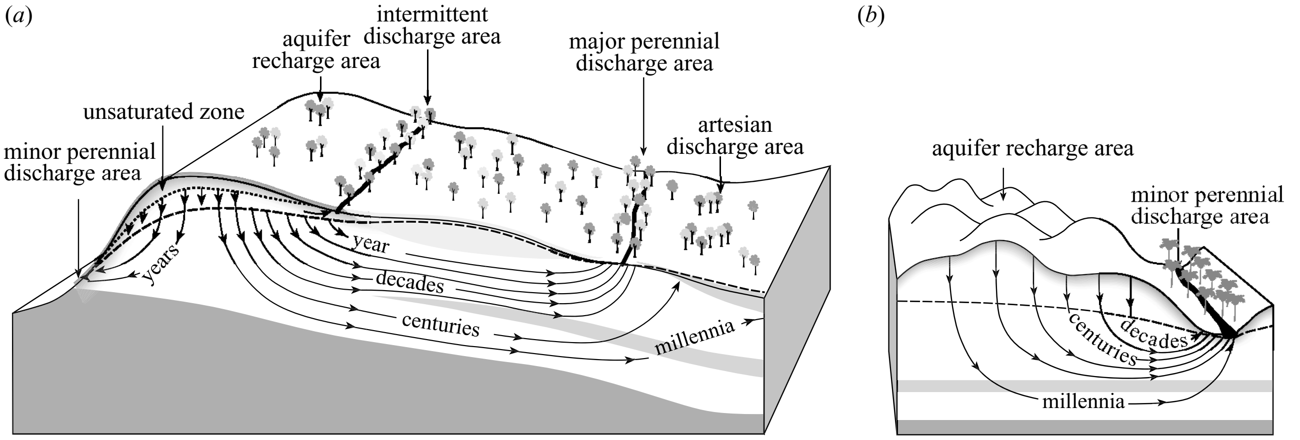


Figure 4. Typical groundwater systems in (*a*) humid regions, and (*b*) semi-arid regions. The residence periods indicated are typical order-of-magnitude values from location of recharge to point of discharge. Dotted line, groundwater; dashed line, piezometric level (with maximum and minimum levels in the non-confined aquifer); light grey areas, aquitard (low permeability strata); dark grey areas, aquitard (virtually impermeable strata).

(i) Changes in land use and vegetation cover, notably introduction of irrigated agriculture with imported surface water (figure 5*a*), but also with natural vegetation clearance and soil compaction.
(ii) The urbanization process (figure 5*b*), and in particular the level of water-mains leakage, the proportion of unsewered (*in situ*) sanitation and the degree of reduction in land-surface permeability.
(iii) Changes in surface water regime, especially diversion of riverflow.
(iv) Lowering of the water table by groundwater abstraction and/or land drainage, leading to increased areas and/or rates of infiltration in some aquifer systems.
(v) Longer-term climatic cycles, there remaining considerable uncertainty over the impacts on groundwater systems of the current global warming trend.

These variations mean that groundwater recharge estimates have to be treated with caution. This situation is often coupled with substantial scientific uncertainty in the quantification of individual recharge components because of inherent hydrogeological complexity and limited monitoring data (Simmers *et al.* 1997). Moreover, the quantification of natural recharge is subject to methodological difficulties due to

(i) the wide spatial and temporal variability of rainfall and run-off events; and
(ii) the widespread lateral variation in soil profiles and hydrogeological conditions.

However, several useful generic observations can be made about aquifer recharge processes.

(i) Areas of increasing aridity will have a much lower rate and frequency of downward flux to the water table, with direct rainfall recharge generally becoming progressively less significant than indirect recharge from surface run-off and incidental artificial recharge arising from human activity (figure 5).
(ii) Estimates of the direct rainfall recharge component are almost always more reliable than those for the indirect component from run-off recharge.

The integrity of the soil layer overlying aquifers plays a key role in allowing groundwater recharge to take place, and anthropogenic influences can be highly significant in this context. For example, there are increasing field observations from across the African Shield that clearance of natural vegetation is leading to soil erosion and compaction. The consequent reduced infiltration decreases aquifer recharge and discharge and dry-weather flow in many smaller rivers, which are vital to human survival and livelihood.

(**b**) ***Consequences of intensive and uncontrolled use***

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 necessary but also desirable (Llamas & Custodio 2002), as it often improves land drainage and maximizes groundwater recharge rates by providing additional subsurface storage space for excess wet-season rainfall.

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

(i) the rate of leakage which can be induced to flow through the confining beds from overlying shallow aquifers; and
(ii) the rate of replenishment of the shallow aquifers from surface infiltration.

This overdraft of aquifer storage can have a series of consequences (table 3), which need to be weighed against the socio-economic benefits of resource development (Foster *et al.* 2000). Most widespread is the incidence of

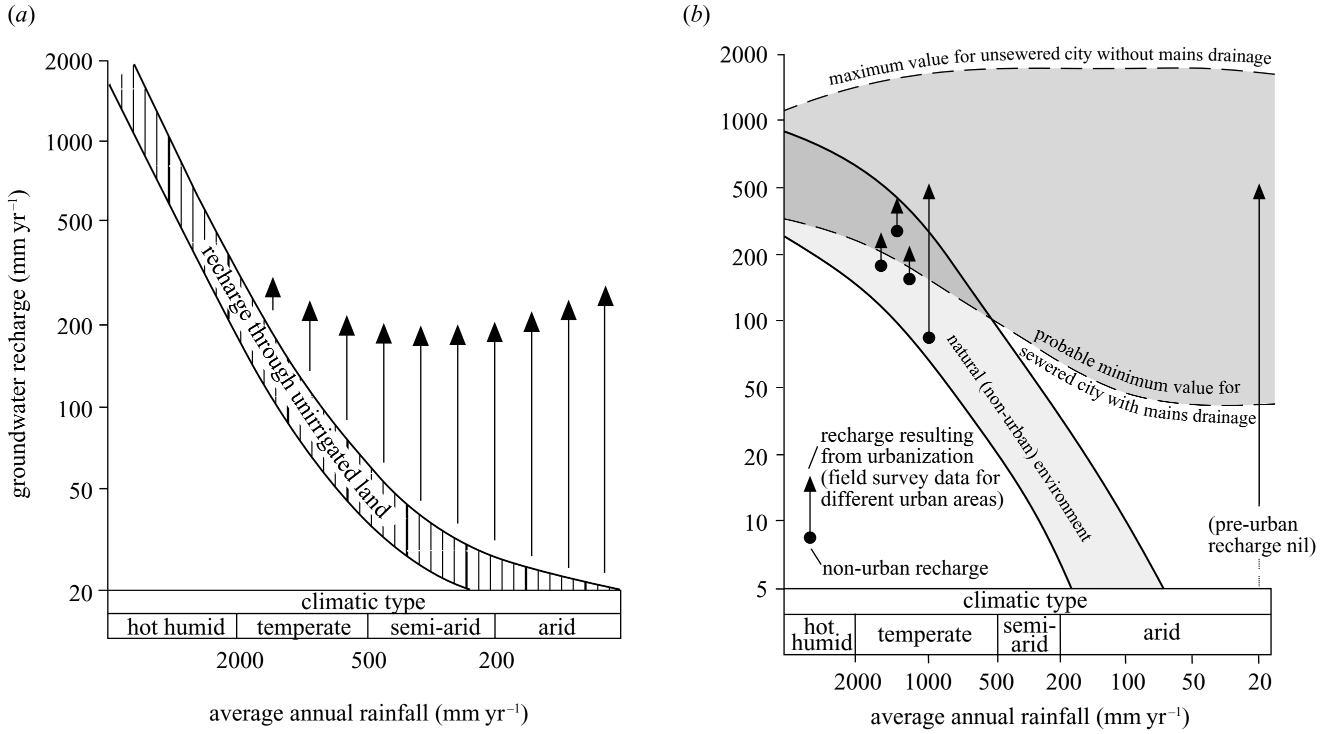


Figure 5. General scheme of variation of groundwater recharge rates under (*a*) irrigated agriculture and (*b*) urbanization. Assumes presence of unconfined aquifer, and effects of increased recharge will be more apparent when imported surface water is primary source of irrigation and urban supply.

competition for available groundwater resources resulting in falling water tables. In thick alluvial and sedimentary aquifers in particular, there is evidence of increasing social inequity where deeper (larger-capacity) boreholes lower the regional water table and increase the cost of (or eliminate access to) water supply for users of shallower wells.

A significant fraction of total aquifer replenishment is commonly required to maintain dry-weather river flows and/or to sustain some types of aquatic and terrestrial ecosystem (Alley 1999). Groundwater abstraction may reduce natural aquifer discharge to the aquatic environment in some cases seriously, and resource development involving consumptive use of groundwater (or export from the sub-basin concerned) has the greater impact. This should be an important consideration in resource planning and environmental management, but it is one that has been overlooked all too often in the past.

In addition more severe, and essentially irreversible, side effects can also occur (table 3). The most notable of these involves the encroachment of saline water, commonly through lateral intrusion from the sea (if coastal hydraulic gradients are reduced or reversed) and from above in layered coastal aquifers. These effects are quasi-irreversible, because the saline water which first invades macropores and fissures diffuses rapidly into the porous aquifer matrix under the prevailing high salinity gradients, but then takes decades to be flushed out, even after the flow of freshwater has been re-established (Foster *et al.* 2000). 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.

(c) *Aquifer depletion due to irrigation usage*

Globally there are important examples of major aquifer depletion as a result of groundwater abstraction for agricultural irrigation, with lowering of the water table over extensive areas. It has been estimated that mining of groundwater reserves is currently occurring at a rate of

(i) some 10 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ on the North China Plain within the Hai He basin (figure 6); and
(ii) *ca.* 5 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ in the 100 or so recognized Mexican aquifers.

The major consumptive use of groundwater on the North China Plain is currently the irrigation of cereal crops, for which a cropping intensity of *ca.* 1.7 is achieved with a combination of (regularly irrigated) winter wheat and (occasionally irrigated) summer maize. The shallow aquifer has experienced water-table decline of more than 15 m in the past 30 years (figure 6) over most of the rural areas of the North China piedmont plain, and stretching onto the alluvial flood plain (Foster *et al.* 2003).

Significant (and in some cases delayed) lowering of groundwater levels is often necessary for major groundwater development (Foster *et al.* 2000). However, in 1988 it was independently estimated for the Hai river basin that average groundwater abstraction exceeded recharge by some 8800 million $\mathrm{m}^3\,\mathrm{yr}^{-1}$. Using a reasonable range of values for specific yield of the strata drained (increasing westward from 0.08–0.18), the long-term water-table decline of 0.5 $\mathrm{m\,yr}^{-1}$ equates to an average recharge deficit of 40–90 $\mathrm{mm\,yr}^{-1}$. It is of relevance to consider the significance of this recharge deficit in terms

Table 3. Consequences of excessive groundwater exploitation.
(The two effects in the middle band may be either reversible or irreversible depending on local conditions and the period during which excessive groundwater abstraction persists.)

consequences of excessive abstraction		factors affecting susceptibility
reversible interference	pumping lifts/costs increase	aquifer response characteristic
	borehole yield reduction	drawdown to productive horizon
	springflow/baseflow reduction	aquifer storage characteristic
	phreatophytic vegetation stress	depth to groundwater table
	aquifer compaction and transmissivity reduction	aquifer compressibility
irreversible deterioration	saline water intrusion	proximity of saline/polluted water
	ingress of polluted water	
	land subsidence and related impacts	vertical compressibility of overlying/interbedded aquitards

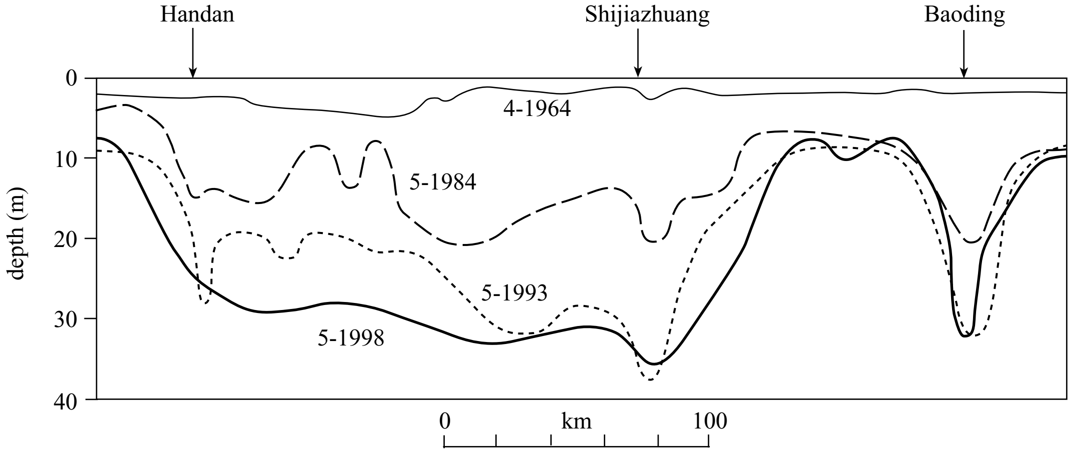


Figure 6. Historical evolution of the water table in the Quaternary aquifer of the North China Plain. These data represent a very long transect in a southerly direction from Beijing across the phreatic piedmont plain aquifer.

of the proportion of cereal cropping dependent upon mining non-renewable groundwater storage reserves. A preliminary estimate, using the limited available data and making various assumptions, suggests that the agricultural production at risk from unsustainable groundwater abstraction is *ca.* 7.0 million $\mathrm{t\,yr^{-1}}$, valued at some US\$840 (CY6720) million $\mathrm{yr^{-1}}$ (table 4).

A nationwide survey of groundwater level trends in India during 1991, based on 'blocks' of some 400–500 $\mathrm{km^2}$, revealed a significant decline in the water table, especially in the more arid western and southern states underlain by weathered bedrock aquifers. These states include Haryana, Tamil Nadu, Rajasthan and Gujarat and the situation in the last of these has been the subject of a detailed review (Burke & Moench 2000). The strong feeling of groundwater ownership of many Indian farmers makes controlling groundwater abstraction difficult, and the authorities are looking to aquifer recharge augmentation to alleviate the situation in some areas. In eastern states (such as Orissa and West Bengal) and in Bangladesh, there is no conclusive evidence of extensive long-term depression of the water table, but competition between deep high-yielding agricultural boreholes and shallow hand-pump domestic wells is a widespread problem.

(d) *Aquifer depletion around major urban centres*

In cities, the overall urbanization process generally increases infiltration rates (Foster *et al.* 1997), but the effect on groundwater levels will depend upon whether

(i) the vertical permeability of strata overlying the main aquifer allow free vertical recharge; or
(ii) abstraction masks the changes in recharge regime.

Where groundwater abstraction is heavy and concentrated, such that it exceeds average rates of local recharge, aquifer water levels may continue to decline over decades, provoking an expensive and inefficient cycle of well deepening or even premature loss of investment through abandonment of wells. Associated major changes in hydraulic head distribution within aquifers may lead to reversal of groundwater flow directions, inducing leakage of polluted water from the surface. Cities located on some types of aquifer may also suffer subsidence. On the cessation of abstraction, the rebound of groundwater levels can have numerous costly impacts on urban buildings and infrastructure and, because of the increased urban recharge, groundwater levels may eventually rise to above the pre-development condition.

Table 4. Assumptions for estimation of potential agro-economic impact of eventual loss of irrigation using non-renewable groundwater reserves.
(The average yield of winter wheat has increased from less than 1000 kg ha^{-1} in the 1950s to more than 4000 kg ha^{-1} in the 1990s, as a result of irrigation with groundwater, improved crop strains, better cultivation techniques and the use of agrochemicals: but if groundwater availability for irrigation was restricted to current average recharge, this could reduce by as much as 50% in a growing season of average rainfall (and more in dry years).)

factor	estimate
current area under cereal cultivation within groundwater resource depletion zone	50 000 km^3
proportion of area with irrigated winter wheat	70%
present average winter wheat yield	4000 kg ha^{-1}
typical unit value of winter wheat	US$120 t^{-1}
probable crop reduction from loss of irrigation water	50%
value of agricultural production at risk from unsustainable groundwater abstraction	US$840 million yr^{-1}

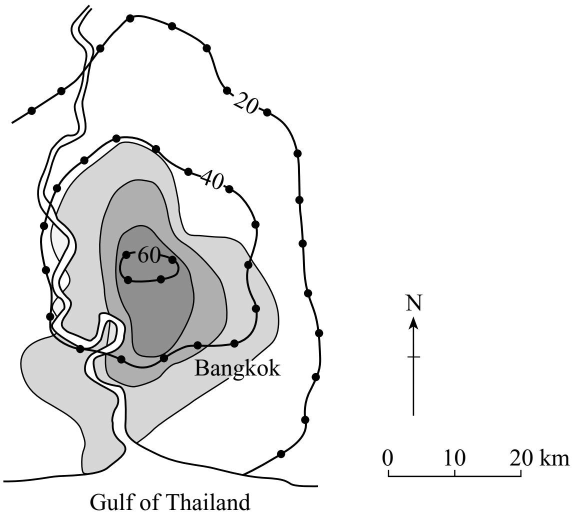


Figure 7. Piezometric depression and land-surface subsidence due to heavy groundwater exploitation in metropolitan Bangkok (modified from BGS 1996). This figure shows the historic evolution; as a result of recent efforts to control and reduce groundwater abstraction in those parts of the urban area also served by surface water supplies, the situation stabilized somewhat during the 1990s. Solid line with circles, depression (in metres) of piezometric surface of confined Nakhon Luang alluvial aquifer in 1987. Shaded areas are cumulative land-surface subsidence to 1987: light grey, 20–40 cm; mid-grey, 40–60 cm; dark grey, 60–80 cm.

Evidence has been accumulating since the early 1970s of substantial and widespread drawdown of the piezometric surface beneath many Asian cities, as a result of heavy exploitation of aquifers. Some cities have experienced extensive depression of the piezometric surface of 30–50 m (including Bangkok, Manila, Tianjin, Tokyo, Shijiazhuang) and many others of 10–30 m (including Beijing, Bandung, Madras, Xian, Shanghai, Tiyuan), and in all of these cases one or more of the above side effects have become serious. Saline intrusion is a widespread problem in coastal aquifers. Land subsidence is a growing problem in some cities, such as Bangkok (figure 7), and has been detected in as many as 45 Chinese cities (Foster & Lawrence 1995).

Elsewhere, Mexico City (population some 25 million) is heavily dependent on groundwater, which has for many years been provided by numerous deep boreholes distributed across the intermontane basin in which the city is located. The resultant drawdown of groundwater levels has been accompanied by serious land subsidence due to settlement of lacustrine deposits, with serious impacts on many buildings. In the Yemen, excessive abstraction for urban water supply and agricultural irrigation around the rapidly growing capital Sana'a has produced water-level declines of 2–3 m yr^{-1} in the underlying aquifers. This has major impacts on pumping costs, but without accompanying land subsidence because the main aquifer is a sandstone. The factors affecting aquifer susceptibility to degradation (table 3) are strongly correlated with aquifer types (figure 2).

3. GROUNDWATER: CONCERNS OVER QUALITY DETERIORATION

Sustainable groundwater development is not only constrained by resource availability but also by quality deterioration (Morris *et al.* 2003). An overall classification of groundwater quality problems based on their genesis is given in table 5. For the purposes of this paper, which is concerned with the degradation of groundwater resources, the discussion is largely restricted to the first two categories—salinization processes and anthropogenic pollution—although this should not be taken as any indication of a lack of appreciation of the importance of the other two categories.

This overview attempts to assess the scale of emerging quality concerns resulting from inadequate management and protection of groundwater resources. In general terms, data on groundwater quality are rather scant, highly dispersed, generally incomplete as regards determinands, and some are of questionable reliability in consequence of inadequate sampling and analytical protocols. An added difficulty is lack of monitoring representativity and sensitivity, resulting from bias introduced by sampling networks which, rather than using purpose-drilled monitoring boreholes and piezometers, are dependent wholly on deep municipal boreholes and shallow domestic wells. The former can be tardy indicators of incipient aquifer pollution due to dilution with older recharge and the latter are often subject to direct wellhead contamination.

(a) *Aquifer salinization: a complex suite of processes*

There are significant areas of the globe where serious groundwater (and soil) salinization are present or have developed as a result of

(i) rising groundwater table, associated with the introduction of inefficient irrigation with imported surface water in areas of inadequate natural drainage;

Table 5. Classification of groundwater quality problems.
(This is based upon the genesis of, or processes underlying, quality deterioration.)

type of problem	causes	parameters of concern
salinization processes	mobilization and/or fractionation of salinity due to inadequate management of groundwater irrigation, mine drainage or petroleum reservoir exploitation; extensive and prolonged surface water irrigation without adequate drainage	Na, Cl and sometimes F, Br, SO_4
anthropogenic pollution	inadequate protection of vulnerable aquifers against man-made discharges/leachates from urban activities and intensification of agricultural cultivation	pathogens, NO_3, NH_4, Cl, SO_4, B, heavy metals, DOC, aromatic and halogenated hydrocarbons, etc. NO_3, Cl, some pesticides and derivatives
wellhead contamination	inadequate well construction and completion, allowing direct ingress of polluted surface water or shallow groundwater	mainly pathogens, NO_3, NH_4, Cl
naturally occurring contamination	related to pH–Eh evolution of groundwater and dissolution of minerals from aquifer matrix (can be aggravated by anthropogenic pollution and/or uncontrolled exploitation)	mainly Fe, F, and sometimes As, I, Mn, Al, Mg, SO_4, Se, and NO_3 (from palaeo-recharge): F and As in particular represent a serious public health hazard for potable supplies

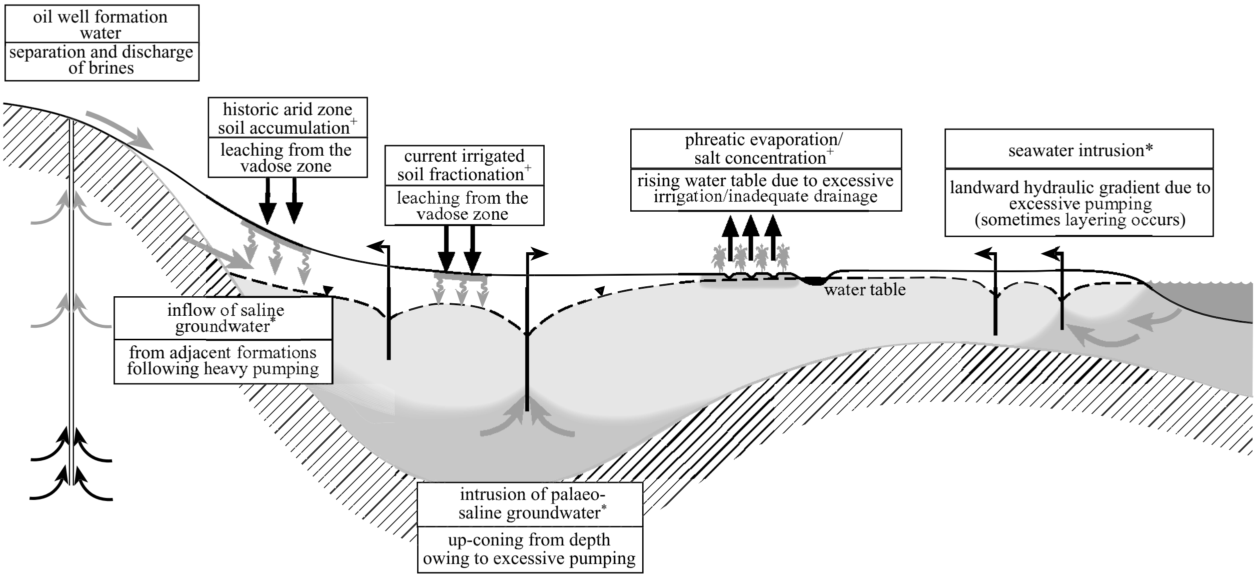


Figure 8. Principal processes causing aquifer salinization. Schematic representation, but in practice normally no more than two or three mechanisms are normally active in any specific case. Those marked with an asterisk are a direct consequence of locally excessive groundwater abstraction but those associated with soil concentration (a plus symbol) are widely distributed. Mid-grey, brackish and saline water; light grey, freshwater.

(ii) natural salinity having been mobilized from the landscape, consequent upon vegetation clearing for farming development with increased rates of groundwater recharge; and
(iii) excessive disturbance of natural groundwater salinity stratification in the ground through uncontrolled well construction and pumping.

These, and other processes, are illustrated in figure 8. All salinization is likely to prove costly to remediate (Foster *et al.* 2000). In the Lower Indus Valley of Pakistan, in probably the largest contiguous surface-water irrigation system in the world, inadequate attention to drainage resulted in 20 000 km^2 of land being severely affected by salinization and another 46 000 km^2 moderately affected, from a commanded area of 140 000 km^2 (Ghassemi *et al.* 1995). Remediation by groundwater drainage to try to lower regional water tables has been underway since the 1960s, at very high investment and operating costs.

'Natural inversions' of the classical salinity–depth profile (with a good freshwater aquifer beneath a body of overlying brackish groundwater) can occur in certain, but quite widely distributed, hydrogeological settings. Such situations are especially susceptible to hydraulic disturbance during groundwater abstraction and require careful diagnosis and management. Two specific examples—from the North China Plain and the Mendoza Northern Oasis, Argentina—are discussed in more detail below.

The entire North China Plain is underlain by a major Quaternary aquifer system, including a deep, semi-

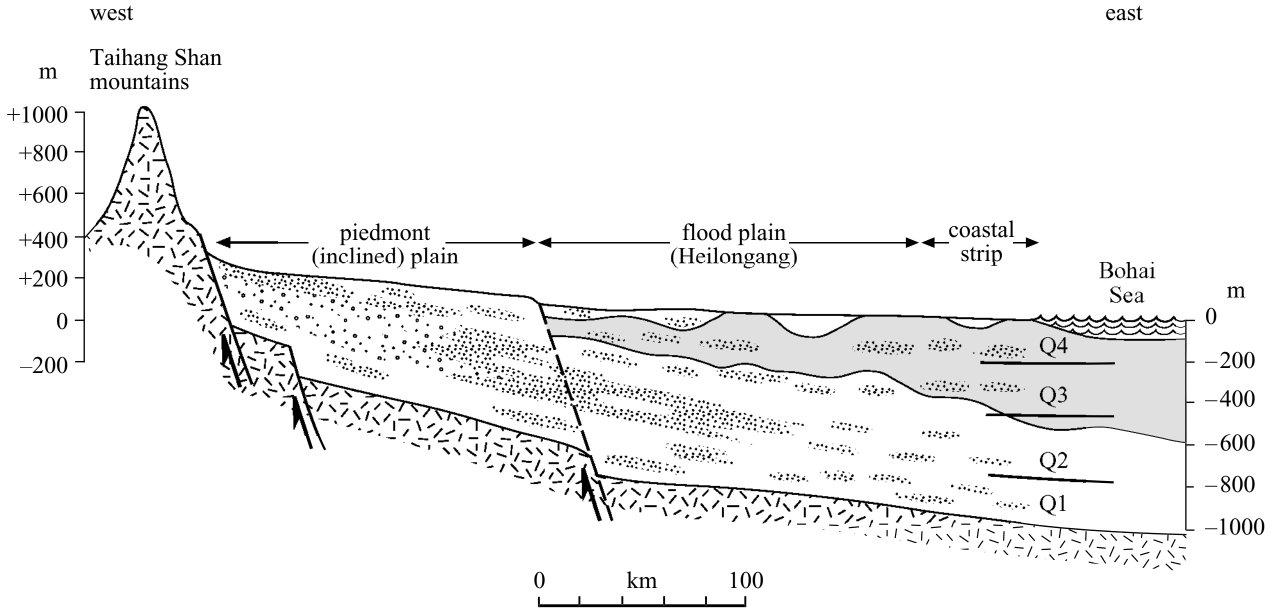


Figure 9. Cross-section of the North China Plain showing the general hydrogeological structure and position of the main body of brackish groundwater. There is a widespread tendency for deterioration of the shallow freshwater aquifer with saline irrigation return water and by upconing of brackish groundwater, and of the deep freshwater aquifer by lowering of the overlying brackish water interface. Light grey area, brackish water; white dotted area, freshwater aquifers (relative grain size indicated); Q1, approximate age of Quaternary deposits.

confined freshwater aquifer of very low salinity beneath an intermediate brackish-water aquifer (Foster *et al.* 2003; figure 9). In recent decades the semi-confined freshwater aquifer has been rapidly developed for urban and industrial water supply, and in some areas (where the shallow freshwater aquifer is thin or absent) for agricultural irrigation. This has resulted in serious salinization and land subsidence at some locations.

There is a definite question of whether any significant freshwater replenishment is reaching the downdip parts of the deep confined aquifer (which has isotopic signatures suggesting recharge in a colder and wetter epoch 10 000–20 000 or more years BP), and a serious risk that inflow of saline water will be induced from the overlying brackish water aquifer if the piezometric surface is heavily drawn-down (Foster *et al.* 2003). There is field evidence from some locations that this latter process has been occurring at rates of 0.5–1.5 m yr^{-1} over the past 20 years.

The Mendoza Northern Oasis is an extensive irrigation area with average rainfall of only 150–200 mm yr^{-1} underlain by a Quaternary aquifer system, which with increasing distance from its upstream margin exhibits marked layering. Groundwater is abstracted to irrigate large areas outside the command of the main irrigation canals and elsewhere to supplement surface water at times of critical crop demand and in years of low river flow. In the subdued interfluve areas, groundwater salinity in the shallowest aquifer (with the water table at 5–15 m depth) increased from 1000–1500 μS cm^{-1} in the 1970s to 4500–5500 μS cm^{-1} by 1995 (figure 10).

More recently farmers have constructed increasingly deeper wells to tap groundwater in the semi-confined aquifers which exhibited excellent quality. However, heavy pumping from these deeper aquifers led to widespread reversal of the natural vertical hydraulic gradient and salinity being drawn down into the second aquifer. This threatens its use for irrigation of high-value, salt-sensitive crops and causes serious yield losses in an area with excellent micro-climate for export-quality viniculture and fruit trees (figure 10).

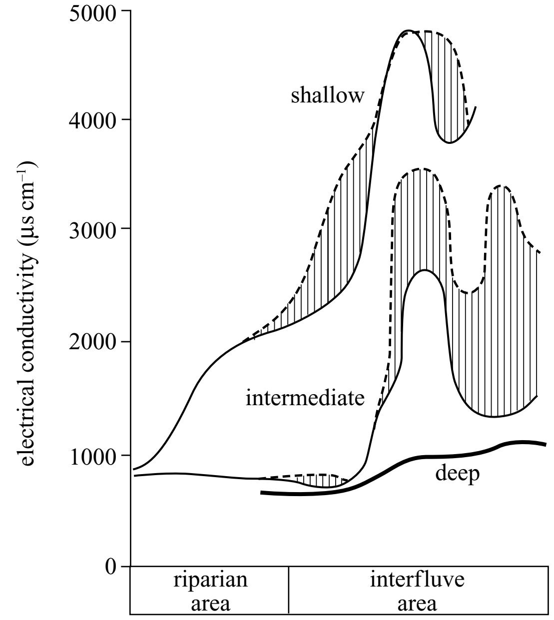


Figure 10. Evolution of groundwater salinity profiles of the Quaternary multi-aquifer system of the Mendoza Northern Oasis, Argentina. Increasing groundwater salinity appears to be the result of salt concentration in irrigation return waters (rather than rising water table and phreatic evapotranspiration), although there is also a component of mobilized salts from the vadose zone when the area was first brought under irrigation. Groundwater electrical conductivity: light solid line, 1979–1983; dotted line, 1992. Horizontal shaded areas, increase over *ca.* 10 years; thick solid line, deep aquifer (little change over period).

(b) *Vulnerability of aquifers to anthropogenic pollution*

Groundwater pollution consequent upon human activity at the land surface has been reported with increasing frequency for more than 40 years in the most industrialized countries and for over the past 20–30 years in the more rapidly developing nations, because of the absence of positive aquifer protection policies (Sampat 2000). Many more incidents are likely to be occurring as yet unobserved, as a result of the generally inadequate level of current groundwater quality monitoring. Although aquifers are much less vulnerable to anthropogenic pollution than surface water bodies, when aquifers become polluted contamination is persistent and difficult to remediate as a result of their large storage, long residence times and physical inaccessibility.

Aquifer pollution vulnerability is a helpful concept (Foster *et al.* 2002), widely used to indicate the degree to which groundwater can be adversely affected by an imposed contaminant load. This is a function of the intrinsic characteristics of the subsoil profile and unsaturated zone or confining beds that separate the saturated aquifer from the land surface immediately above.

The ability of natural subsoil profiles to attenuate many water pollutants has long been implicitly recognized by the widespread use of the subsurface as a potentially effective system for the safe disposal of human excreta and domestic wastewater. However, not all soil profiles are equally effective in pollutant attenuation. Some aquifers are thus more vulnerable than others, and can be affected by a wide range of pollutants discharged or leached at the land surface. Moreover, even deeper, semi-confined aquifers will (sooner or later) be affected by relatively persistent contaminants (such as nitrate, salinity and certain synthetic organics), if widely leached into groundwater in aquifer recharge areas. An important factor that contributes to groundwater pollution hazard and complicates its assessment in consolidated (and fractured) strata is the possibility that downward transport can occur through preferential pathways, which greatly increases the vulnerability to contaminants that would otherwise be retarded by adsorption and/or eliminated by biodegradation (figure 11).

The more spectacular groundwater pollution incidents, with large plumes of high concentration, are associated with industrial point sources from major accidental spillage or casual discharge in highly vulnerable areas. However, more insidious and persistent problems are associated with unsewered urban and industrial development and with diffuse pollution generated through intensification of agricultural cultivation (Foster *et al.* 2002). Although certain clear tendencies have been identified, including most notably the widespread quality deterioration of shallow vulnerable aquifers in areas of rapid urbanization and agricultural intensification, it is not generally possible to make reliable estimates of the proportion of active replenishment or of groundwater storage affected by pollution. This is because few nations have groundwater quality monitoring networks adequate for this purpose.

(c) *Impacts of urbanization and industrialization*

Most future growth of urban areas will be concentrated in the less-developed nations. Demographic growth in Asia has been concentrated in urban centres and there are now some 14 cities with populations in excess of four million and 70 with populations in excess of one million. The rapid growth in urban population has generally outstripped the provision of water supply, sanitation and refuse disposal, especially in marginal districts.

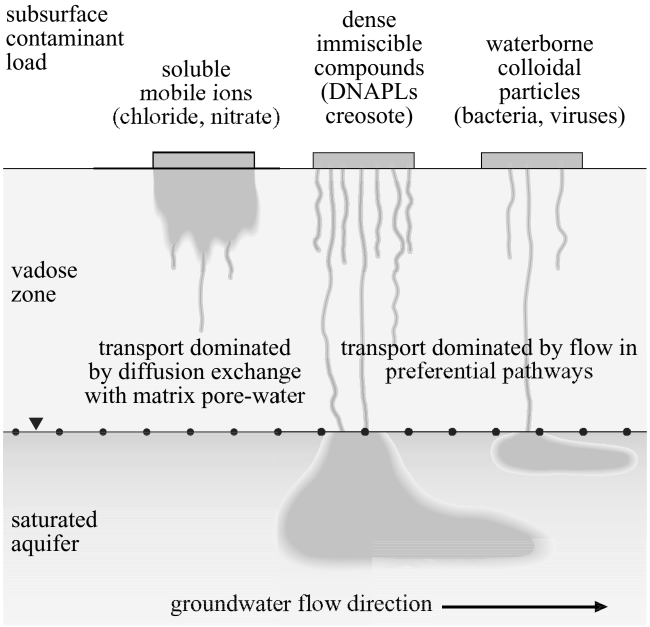


Figure 11. Schematic illustration of the occurrence and consequences of vadose zone preferential flow in terms of increasing the pollution vulnerability of an aquifer. It is noteworthy that in many formations subject to preferential flow, the vulnerability to pollution by pathogenic micro-organisms and immiscible organic compounds is markedly increased relative to the penetration of normal aqueous-phase dissolved contaminants.

Urbanization, coupled with its associated industrial development, has profound impacts on the hydrological cycle, including major, but not always readily identified, changes in the frequency, volume and quality of groundwater recharge (figure 5*b*), modifying existing recharge mechanisms and introducing new ones (Foster *et al.* 1997). These are a result of the importation of large volumes of water from the surrounding areas to meet urban demands (figure 5*b*), together with the widespread reduction in permeability of the land surface and consequent diversion of run-off and drainage by the construction of roofs and paved areas.

If sanitation is achieved through on-site arrangements (such as soakaways, septic tanks, cesspools and latrines) urbanization will lead to major increases in the overall groundwater recharge rate (figure 5*b*). This may, however, be accompanied by significant deterioration in groundwater quality as a result of increasing concentrations of nitrate (figure 12), organic carbon (including the possibility of toxic synthetic compounds) and, in certain hydrogeological conditions and/or with inadequate sanitation design, to contamination with pathogenic bacteria and viruses.

In those areas where a significant proportion of the wastewater disposal is by mains sewerage, large volumes of minimally treated wastewater are generated. In the more arid climates in particular, this wastewater is widely used

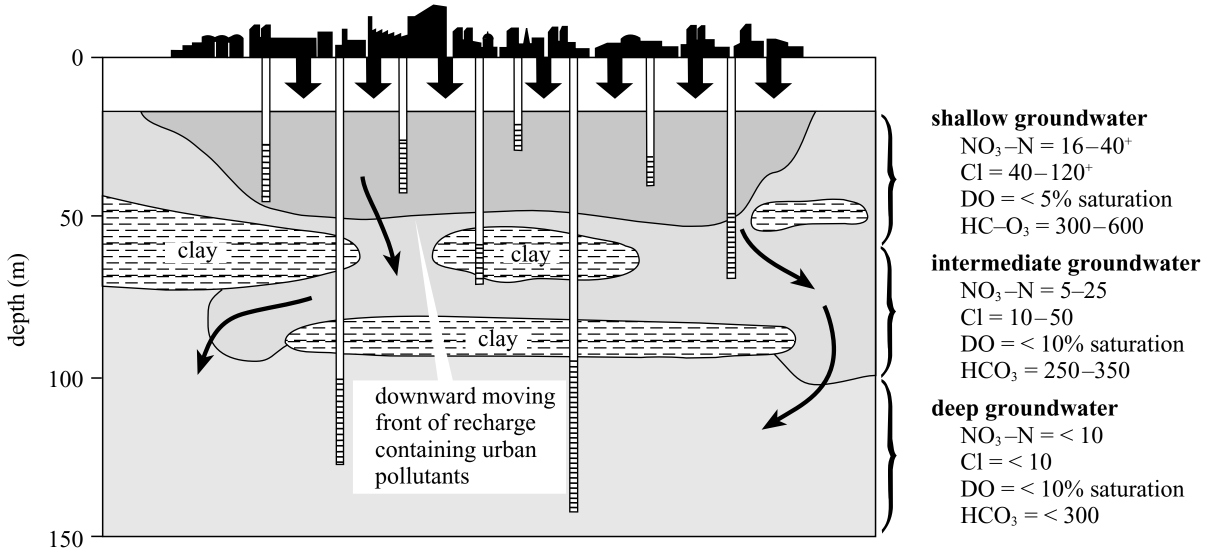


Figure 12. Impact of rapid urbanization on shallow groundwater quality in the alluvial piedmont plain aquifer beneath Santa Cruz-Bolivia (modified from Foster *et al.* 1997). The impact is most revealed by elevated nitrate and chloride concentrations, but consumption of dissolved oxygen through the organic carbon loading is also present leading to the likelihood of dissolution of iron (and possibly other metals) from the aquifer matrix.

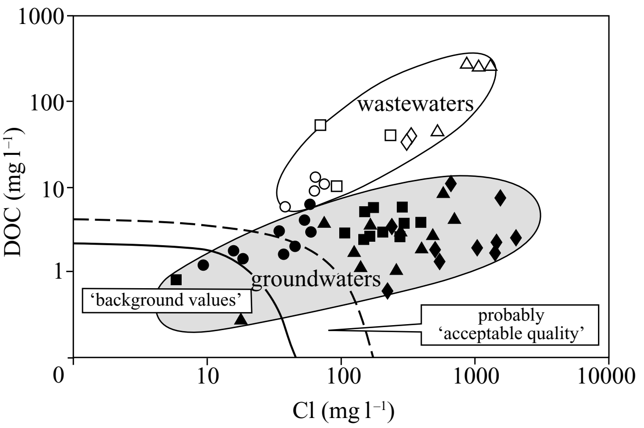


Figure 13. Range of groundwater DOC and Cl concentrations in shallow aquifers below major areas of wastewater reuse for agricultural irrigation. Squares, Mezquital, Mexico; triangles, Leon, Mexico; circles, Hat Yai, Thailand; diamonds, Wadi Dhuleil, Jordan.

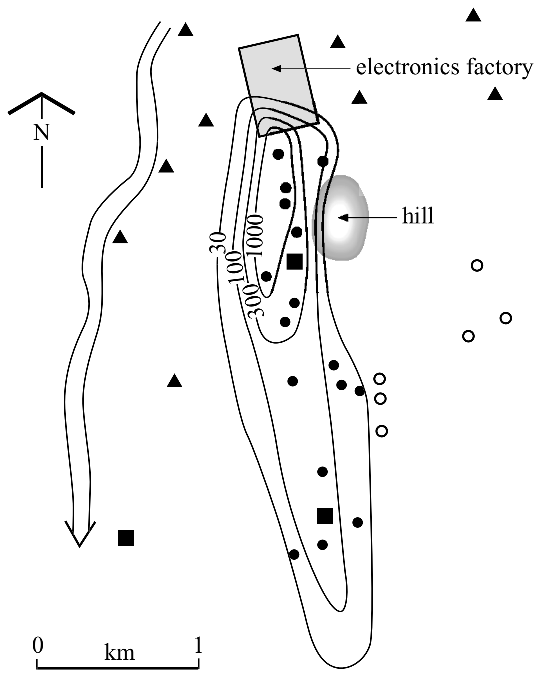


Figure 14. TCE plume detected in alluvial aquifer of a Japanese city resulting from a leaking underground storage tank at an industrial site (modified from Hirata *et al.* 1992). The groundwater pollution in a highly permeable alluvial aquifer system is well defined, although the processes (pollutant breakdown, absorption and dilution) reducing the advance of the plume are not fully understood. Squares, public water-supply well. Shallow monitoring wells where: triangles, TCE not detected; white circles, TCE less than 30 $\mu g\, l^{-1}$; black circles, TCE more than 30 $\mu g\, l^{-1}$ (WHO guideline for potable water); lines with numbers, TCE concentration ($\mu g\, l^{-1}$) in shallow groundwater.

for agricultural irrigation. Because irrigation efficiencies with wastewater are invariably low, high rates of incidental infiltration and aquifer artificial recharge result. This represents simultaneously a resource benefit and a pollution hazard (figure 13), and requires (but rarely yet receives) careful management.

The rate of industrialization in most countries continues apace, and even in less-industrialized nations there are often numerous small-scale industries, notably textile and leather, which generate significant contaminant loads. Many industrial activities are located in peri-urban areas, which remain unsewered, and industries generating liquid effluents (including spent oils and solvents) often dispose of them to the ground. The accidental spillage and leakage of industrial chemicals also causes serious, but more localized, groundwater pollution. In a survey of 15 Japanese cities (Foster & Lawrence 1995) chlorinated solvents were detected in *ca.* 30% of all wells tested, and at sites of some major automobile and electronics manufacturing major pollution plumes have been detected (figure 14).

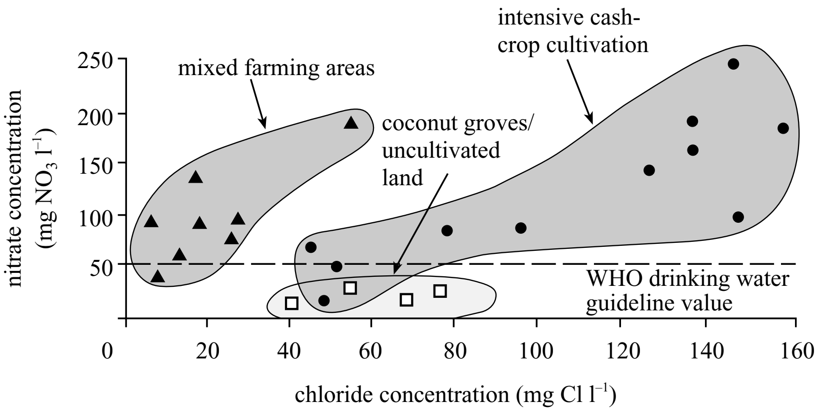


Figure 15. Variation of shallow groundwater quality in recent coastal limestone aquifer of western Sri Lanka with overlying agricultural activities (modified from BGS 1996). Intensive irrigated horticulture is being introduced on permeable sandy soils over a shallow calcareous aquifer with triple cropping sustained by applications of up to 500 kg N ha^{-1}. It is estimated that an equivalent to 70% of the fertilizer nitrogen application was being leached to groundwater after taking account of the recycling of nitrate in irrigation water.

(d) *Impacts of agricultural intensification*

Over the past 20–50 years there has been a radical evolution in agronomic practice in many regions of the world associated with largely successful attempts to increase agricultural productivity. The intensification of production from agricultural land has been sustained by the application of ever-increasing quantities of inorganic fertilizers and a wide spectrum of synthetic pesticides. In the more arid regions, cropping frequency has been increased and additional land has been brought into production through new irrigation schemes and increasing irrigation efficiency.

A common trend is the replacement of traditional crop rotations by intensive near-monoculture of individual crops (selected according to prevailing market conditions) across extensive tracts of agricultural land. There is a risk of elevated rates of nutrient, salt and pesticide leaching from intensively cultivated soils to groundwater. In many nations the principal recharge areas of lowland aquifers are now almost completely used for intensive crop cultivation (Foster & Chilton 1998). In such cases the bulk of groundwater resource replenishment originates as excess rainfall and excess irrigation (figure 4*b*) infiltrating this land. As a consequence, groundwater is vulnerable to contamination by cultivation practices.

Fertilizer usage has shown steadily rising trends in China and India, where application rates in some areas now approach those of similar agricultural regimes in Europe. Close correlations between high nitrate concentrations in shallow groundwater and intensive agricultural cultivation have been increasingly widely reported (figure 15), and sometimes attributed to the direct losses of fertilizer nitrogen. This, in itself, is somewhat misleading because it is the effect of cultivation practices on the soil nitrogen pool and rates of nitrate generation and leaching from this pool (only a minor part of which is directly derived from inorganic fertilizers) that are, in reality, the key processes.

In situ natural denitrification in aquifer systems has been the subject of considerable research (Korom 1992), because it results in removal of nitrate from groundwater. The process is likely to be bacteriologically mediated, and clear evidence of appropriate bacteria has been found; but it could also be chemical, accompanying the oxidation of disseminated pyrite found in many geological formations. Clear evidence of denitrification comes from many confined aquifers. But in the vadose zone, the generally aerobic conditions imply that denitrification cannot be widely active, despite the presence of some potentially denitrifying bacteria, but it may be more significant in the zone of water-table fluctuation.

All pesticide compounds pose a significant environmental health hazard as they are, to greater or lesser degree, chemically tailored to be toxic and persistent. However, before 1980, there was not much concern about the possibility of groundwater pollution by pesticides, because agricultural scientists argued that soil sorption of the higher molecular mass compounds (such as the chlorinated hydrocarbon insecticides) and volatilization of lower molecular mass compounds (like most herbicides) would be the dominant attenuation processes. However, the key factors in determining whether pesticide residues will be leached to groundwater are primarily the mobility of the compound and secondarily its persistence (Foster & Chilton 1998).

The degradability of pesticide compounds in the soil will normally be significant and soil half-lives for most compounds currently in widespread use range from 10 days to a few years. For the more mobile compounds they are normally less than 100 days, but they are sufficiently persistent to remain in the soil for significant periods when leaching may occur. Published pesticide half-lives apply to fertile soils, but rates of chemical breakdown and biological degradation in the deeper subsurface are likely to be many orders-of-magnitude slower. Moreover, some derivatives of partial oxidation or hydrolysis (metabolites) may be equally toxic and/or mobile as the original pesticide compounds themselves (Kolpin & Goolsby 1995). Thus degradability is of less significance than mobility in assessing the potential hazard for groundwater, and soil profiles which favour preferential flow through the vadose zone (figure 10) are of special concern in relation to potential groundwater contamination.

There are very scant data on which to judge the current level of pesticide penetration to groundwater systems, especially in the developing nations, although the most vulnerable hydrogeological environments can be identified with reasonable confidence. Investigations to appraise adequately the level of pesticide leaching to groundwater are proving costly and problematic because of

(i) the wide range of pesticide compounds in common use, many of which break down to toxic and persistent derivatives; and
(ii) the need to work at low concentrations because of the high toxicity of many compounds, which necessitates careful sampling to avoid compound modification and volatile loss.

Because of these difficulties, an essential prerequisite is to identify the most likely types and sources of pesticide contamination and the most probable mechanisms of transport from the land surface to groundwater. Such information is essential for the specification of sampling protocols and monitoring networks, and to prioritize investigation work (Foster & Chilton 1998).

Where irrigation is practised, it is possible to control soil moisture to maximize nutrient uptake and restrict deep percolation, thereby controlling the leaching of agrochemicals. This is most practicable where most plant moisture is provided by irrigation and where the wet season is confined within a few months each year. It is less feasible where irrigation is required mainly to secure a second crop, but even here the maximization of nitrate uptake can be assured by providing optimum moisture levels at times of rapid plant growth, and thereby reduce soil nutrient residues. Moreover, denitrification losses become more significant in irrigated cultivation, at least on finer-grained soils. Highly efficient irrigation techniques offer the potential for greater control over soil leaching, but groundwater recharge will be of reduced volume and progressively more saline. However, for the present, many irrigation practices remain relatively inefficient, with excess moisture applied by each irrigation lamina and regular soil leaching resulting.

4. GROUNDWATER RESOURCES: A SUMMARY OF FUTURE IMPLICATIONS

(a) *Status of global groundwater resources*

Groundwater is a key natural resource supporting economic development, but is still widely under-valued, inefficiently exploited and inadequately protected. With the pressing need for rapid development of new water supplies, adequate attention is rarely given to resource conservation and protection, despite the fact that in the longer term this can be a serious constraint on sustainable development. Far too few of the huge benefits of groundwater development have been reinvested in the management of the resource base. Many nations need to appreciate their social and economic dependency on groundwater, and to invest in strengthening institutional provisions and building institutional capacity for its improved management, before it is too late and groundwater resources are irrevocably degraded.

The first major concern is the sustainability, in both quantity and quality terms, of groundwater supplies in some intensively cultivated agricultural areas, especially where these are located on aquifers susceptible to the irreversible side effects of uncontrolled exploitation and/or highly vulnerable to pollution. The second major concern is marked quality deterioration in shallow groundwater around many cities, which is the result of indiscriminate use of the ground for the disposal of a wide range of liquid effluents and solid residues. The situation is aggravated by the side effects of generally uncontrolled aquifer exploitation, and by the piecemeal approach to water infrastructure development that has been taken all too often in the past. There are incipient signs of similar tendencies in some of the very many medium-sized towns, wholly dependent on groundwater for municipal water supply.

Monitoring of aquifer abstraction and use, water-level fluctuation and recharge quality is, for the most part, far from adequate to meet the information needs of water resources management. Unlike surface water monitoring, each groundwater observation is a local sample of aquifer state, rather than an integrated measure of river-basin response. To provide adequate spatial characterization of groundwater quality, many sampling points may be required, and the consequent expense is an important discouragement to establishing good monitoring programmes for groundwater. The sparseness of reliable existing data reduces current ability to present a comprehensive and well-substantiated statement on the global status of groundwater resources, and more broadly the role of groundwater in some processes of global change.

Nevertheless, in some areas extensive aquifer degradation has been only too well proved, and in numerous others there is evidence of significant deterioration. The slow groundwater flow rates and very large storage within most aquifer systems has important implications.

(i) Most existing resources originated as recharge before recent land-use changes and are of good quality.
(ii) The deterioration of groundwater quality is gradual, and may not be recognized until large volumes have been affected.
(iii) Monitoring needs to focus on providing data on contemporary groundwater recharge quality, as it is this that will replace the stocks of generally much older (high quality) groundwater in aquifers: thus providing an ‘early warning’ of future problems.

(b) *Approaches to the management challenge*

The diversity of groundwater occurrence, coupled with changing patterns of human use of water and land, present a complex mosaic within which resource management and protection have to function, and dictate that no simple blueprint for management action is realistic. For example, low-intensity rural use can sit side-by-side with intensive urban abstraction in the same aquifer. At the same time, macro-economic drivers of groundwater demand may come into play—which can be as diverse (and on occasions perverse) as agricultural subsidies and flat-rate rural electricity tariffs—and these need to be reformed because they provide no incentive to reduce groundwater pumping.

A key institutional requirement in many countries for improving groundwater management at field-level will be to transform the role of the government agencies responsible for groundwater from exclusively 'supply-development' to primarily 'resource-custodian' and 'information-provider' (Foster *et al.* 2000), and to ensure that such agencies fully engage groundwater users and stakeholders in a participatory management process.

A major challenge for the future is to stabilize aquifers exhibiting serious hydraulic imbalance, and where feasible reinstate some discharge to the surface water environment. This can only be achieved by implementing demand management measures. This variously requires (Foster & Kemper 2003):

(i) an institutional framework of appropriate style and scale;
(ii) a sound system of groundwater abstraction and use rights;
(iii) adequate financial investment in water-saving technology;
(iv) active groundwater user and broader stakeholder participation; and
(v) economic instruments to encourage reduced water consumption.

Rainwater harvesting and aquifer recharge enhancement have only recently been approached on a systematic and proactive basis in some countries. They require adequate incentives to local landowners and groundwater users, together with good planning, design, operation and appropriate monitoring to ensure the selected method is effective and sustainable. A range of potentially cost-effective methods is available for 'banking' either excess rainwater, surface run-off and reclaimed wastewater in aquifers.

In relation to groundwater pollution threats, the major management task is one of protection. This requires sustained institutional action to identify 'hazardous activities' and 'vulnerable areas'. Aquifer and groundwater supply pollution protection requires making groundwater more visible to stakeholders and the broader public, and thereby mobilizing their participation in pollution control.

The principal problems that have arisen in relation to groundwater in urban development (Foster *et al.* 1997) result from the common failure by urban water and environmental managers:

(i) to identify and manage potentially negative interactions between wastewater elimination and groundwater supply; and
(ii) to recognize the association between groundwater abstraction and urban drainage and infrastructure in low-lying cities.

There is an urgent need for rapid surveys of groundwater use, aquifer pollution vulnerability and subsurface contaminant load, to be undertaken. Groundwater pollution risk and susceptibility to overexploitation effects can then be assessed and protection measures prioritized and initiated.

The degradation of groundwater in the agricultural environment stems from the innumerable, small, everyday activities and decisions made by farmers. Individually these activities may not cause discernible harm, but their aggregation over years can combine to affect groundwater adversely. A rational strategy for the control of diffuse groundwater pollution from agricultural cultivation practices would need to include the following measures (Foster & Chilton 1998).

(i) Recognition that some incremental changes in agricultural cultivation run a high risk of adverse impact on groundwater quality, while offering only marginal returns to farmers.
(ii) Adoption of major aquifer recharge areas as a separate unit in guidelines for agronomic practice, taking account of the need to reduce leaching to groundwater.
(iii) Introduction of groundwater leaching assessments into cropping trials before new agronomic practices are recommended and pesticide compounds approved.
(iv) Acceptance that more positive control over land use may have to be taken in groundwater source protection areas.

This paper takes the form of a broadly based review of international understanding. The authors are indebted to numerous colleagues in the World Bank: Groundwater Management Advisory Team (GW-MATE) and in the British Geological Survey: Groundwater Surveys and Water Quality Programme, together with Jacob Burke of the UN Food and Agriculture Organization, for information and insight on this subject. However, the opinions expressed in the paper are those of the authors alone and not necessarily of the World Bank or its affiliated organizations nor of the British Geological Survey.

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GLOSSARY

DNAPL: dissolved non-aqueous phase liquid
DO: dissolved oxygen
DOC: dissolved organic carbon
TCE: trichloroethylene