PROTECTING RURAL GROUNDWATER QUALITY

7

ROLE OF GROUNDWATER IN RURAL AREAS

The importance of groundwater for both domestic and agricultural use in rural areas was highlighted in Chapter 1, where we stressed its ability to provide farms and small rural communities with simple supplies relatively cheaply, in close proximity to the users and commonly without the need for complex treatment. Thus, in the United States, more than 95 per cent of the rural population depends on groundwater for domestic supply, often from individual farmstead boreholes.

In Asia most of the largest countries—India, Pakistan, China, Bangladesh, Indonesia, Thailand and Vietnam—are more than 50 per cent dependent on groundwater for potable supplies and the advantages of groundwater highlighted in Chapter 1 make it more dominant in the rural areas. The traditional source of domestic water in many rural areas in the Middle East and on the Indian subcontinent has been groundwater drawn from large diameter hand-dug wells. These wells are still widely used, although in more recent years drilled boreholes, fitted with hand pumps, have become popular. Groundwater accounts for over 80 per cent of the domestic water supply in rural India (much of it from three million wells equipped with hand-pumps) and 50 per cent of irrigation requirements from more than 16 million motor-driven pumps installed on both boreholes and dug wells.

A similar picture applies in Central and South America, where in addition to the dependence of some of the largest cities mentioned in Chapter 1, groundwater use is vital in smaller towns and rural areas. Mexico, Peru and Chile obtain more than half of their potable supplies from groundwater and for most of the other countries of the region the figure is between 25 and 50 per cent. Groundwater is also very important for agriculture in all of these regions.

In sub-Saharan Africa, although poorly permeable rocks occupy a significant part of the subcontinent and only limited yields to wells and boreholes are possible, rural shallow aquifers remain the only technically and economically feasible source of reliable supplies of acceptable quality water, especially where perennial surface water sources are lacking. As Table 27 shows, four of the main hydrogeological settings described in Chapter 2 form much of sub-Saharan Africa. The hydrogeological conditions of low permeability combined with limited storage in the first three settings are such that groundwater resources in the region, while usually adequate for domestic use, are sometimes difficult to locate and develop, and are rarely adequate to support other than very small-scale irrigation. Nevertheless, many African countries have low per capita water availabilities so the resource is vital because very large proportions of the several hundred million people living on the rocks of each type are rural and depend on groundwater for their domestic supply.

Table 27 Hydrogeological settings and dependent populations in sub-Saharan Africa

Hydrogeological setting	Proportion of total area (%)	Population (millions)
Weathered basement complex	40	220
Extensive volcanic terrains	6	45
Consolidated sedimentary rocks	32	110
Unconsolidated sediments	22	60

A key sustainability concern is the growing inter-relationship between urban and rural groundwater resources. Three features characterise the rural-urban interface:

i As outlined in Chapter 5, the rapid growth of cities is accompanied by greatly increased demand for water. While cities and towns gradually extend their dependence for all or part of their supply to well fields in adjacent rural and peri-urban areas, future demand may increasingly force them to look further and further afield. The general large differential in water pricing between adjacent urban and rural areas usually gives the municipal water utility sufficient economic strength, institutional powers and political influence to invest in new supplies. In the ensuing competition for the use of scarce groundwater resources, rural domestic users and even large-scale irrigators, whose pricing structure will often have undervalued the groundwater they use, are likely to have a difficult and contentious time.

ii Secondly, spreading urban and peri-urban housing and industrial development may envelop existing well fields and the change in landuse and activities on the catchment surface will increase the hazards to groundwater and strengthen the need for their protection. Even where new well fields are remote from the urban area they may require protection measures imposed around them to constrain the agricultural activities of the existing rural communities.

iii Thirdly, growing urban areas generate increasing volumes of waste water that their sewerage systems collect and deliver as a constant untreated or partially treated stream to downstream riparian rural areas.

POLLUTION THREATS TO GROUNDWATER IN RURAL AREAS

There is no doubt that the intensification of agriculture during the second half of the twentieth century has brought enormous benefits in terms of global food security. Steadily increasing arable productivity has been underpinned *inter alia* by the rapid extension of irrigation, fertiliser application and improved pest control. Yet the unquestioned increases in productivity have also had unanticipated adverse impacts on the quality of underlying groundwater. For instance, in both Europe and North America, extensive research has demonstrated the linkage between expanding cultivated areas, increasing unit fertiliser use and rising groundwater nitrate concentrations. There is now growing concern in many developing countries in which agriculture is a prime part of the economy, and where the benefits to farmers' livelihoods are great.

When assessing the impact that diffuse agricultural pollution can have on groundwater, several factors need to be considered:

i Cultivation often occurs over extensive areas of the aquifer outcrop and thus can potentially lead to widespread pollution of the groundwater. Such diffuse pollution is less intense than that associated, for example, with disposal of industrial wastes or spillages of solvents and fuel oils, and other point sources. Nevertheless the total loadings may be high, and the resultant groundwater concentrations may significantly exceed drinking water guideline values in the most intensively cultivated areas.

ii The use of the groundwater is important; if the aquifer is used for irrigation or industrial/power plant cooling water (or other non-sensitive use) then the impact will be far less serious than when it is used for drinking water. The cost of treating groundwater to remove nitrate and pesticides in excess of guideline limits is expensive and is really only likely to be an option in high-income developed countries prepared to pay the true economic cost of such treatment.

iii Whether alternative sources of water are available and at what cost. However, caution is required especially where deeper semi confined aquifers are considered as alternative sources of freshwater. Development of such aquifers may induce significant downward leakage from shallow groundwater causing contamination of the deeper aquifers in the long term. The use of these deeper aquifers could however 'buy time', allowing measures to be introduced to reduce nutrient, pesticide or saline leaching from the soil. If managed effectively, in the longer term the combination of reduced leaching losses and the dilution effects of using deep aquifer storage could keep problem contaminant concentrations within acceptable limits, but inaction will merely delay the need to take control measures, and may make such measures more expensive.

It is clearly important that the risks to groundwater quality posed by the intensification of agriculture should be assessed, so that any necessary control measures can be introduced. This chapter first describes three major threats to groundwater quality arising from the intensification of agriculture:

- the issue of salinisation of soils due to inadequate irrigation water management;

- the problem of nutrients (principally nitrogen) applied to soils to stimulate plant growth but inadvertently leached to aquifers;

- the as yet poorly quantified risk of pesticide leaching, especially in tropical soils and climates.

In addition, global efforts to close the gap between sanitation coverage and water supply provision will inevitably increase the potential for both on-site sanitation and collected municipal waste water to cause groundwater pollution. While these activities straddle the urban–peri-urban–rural interface, they are included in this chapter, which thus covers those human activities whose impact is most felt by rural communities and the aquifers on which they depend.

Of these, salinisation of soils and groundwater is probably the most widespread and with the greatest environmental and economic impacts.

SALINISATION PROBLEMS

SCALE AND EXTENT OF SALINISATION

Increasing salinity from the effects of irrigation is probably the most important and widespread form of groundwater quality degradation. It is by no means a recent phenomenon, but dates from way back in history. Six thousand years ago the Sumerians of the Tigris-Euphrates floodplain of Mesopotamia grew to prominence on the basis of irrigated agriculture, but the gradual build up of salt in the soil and water inhibited food production and contributed to the eventual decline of their culture. Moreover, the environmental damage to the lower flood plain was such that the subsequent Babylonian and Assyrian cultures were established further north in the upper parts of the Tigris and Euphrates valleys. In the American south-west, the decline of Indian civilisations centuries ago is also attributed partly to salinisation of soil and water, together with damage caused by siltation and catastrophic flooding.

Deterioration of soil and groundwater quality linked to irrigated agriculture continues to the present day, and causes major environmental damage and consequent economic loss to affected farmers and rural communities. Waterlogging and salinisation is a common feature of irrigated lands around the world because the construction of proper and adequate drainage measures was often ignored or postponed, rather than being implemented at the same time as the water distribution system. While this was often a simple engineering and financial decision that has subsequently turned out to be enormously costly, it was in some cases exacerbated if responsibilities for irrigation and drainage rested with different institutions.

The total area of land in the world that is commandable and equipped to be irrigated is now about 275 million ha. Most of this is cropped, but some is temporarily fallow or out of production for reclamation or other reasons. The total area cropped is about 255 million ha, some 80 per cent of which lies in arid and semi-arid subtropical zones, and about 75 per cent is located in developing countries. Only 15 per cent lies within the more humid tropics and 5 per cent in temperate climates. Estimates of the area impacted by salinity are more difficult and they vary, but it seems likely that up to half of world's irrigated land has been affected to some extent by waterlogging, salinity and alkalinity. Salinity seriously affects productivity on about 22 million ha of land and has less severe impacts on another 55 million. The world's worst affected areas are shown in Table 28.

In practice these figures, which are based on FAO statistics for the late 1980s, are difficult to estimate and the situation is not, of course, stable. Important areas of land are continuing to lose productivity in India, China, Pakistan, Central Asia and the United States. The consequent economic cost is also difficult to estimate, but the affected farmers may be losing up to 11 billion US dollars per year. What is certain is that this figure will continue to grow, as salinity problems are spreading to an additional 1.5 to 2 million hectares each year, which may be offsetting up to half of the increased productivity from new land brought under irrigation. While many of the worst affected areas are in the developing world, even richer economies are

Table 28 Areas under irrigation that are affected by salinity in selected countries (Ghassemi et al., 1995)

Country	Irrigated area		Area affected by salinity	
	Million hectares	Share of total cropland (%)	Million hectares	Share of total irrigated land (%)
China	44.8	46.2	6.7	15
India	42.1	24.9	7.0	17
Commonwealth of the Independent States	20.5	8.8	3.7	18
United States	18.1	9.5	4.2	23
Pakistan	16.1	77.5	4.2	26
Iran	5.7	38.7	1.7	30
Egypt	2.7	100	0.9	33

not immune from the consequences of salinisation, and losses in both the San Joaquin and Colorado valleys of the United States reach hundreds of millions of US dollars each year.

MECHANISMS OF SALINISATION

While several mechanisms contribute to the linked problems of waterlogging and salinisation, the underlying cause is the collection and conveyance of large volumes of water and its application to the land for crop irrigation. Poor planning and implementation of irrigation schemes and their subsequent mismanagement reduce the ‘efficiency’ of most irrigation, ie the proportion of the applied water that is actually used in crop production. Enormous water losses occur through canal leakage, infiltration and runoff of water applied in excess and through evaporation from irrigated fields.

Of the total amount applied to the fields, as little as 30 to 40 per cent may actually be used by the growing crops. The remainder leaves the fields as surface runoff, percolates below the crop root zone towards the water table or evaporates directly into the atmosphere. When water evaporates, the dissolved salts are left in the ground, increasing the salts in the soil in direct proportion to the salt content of the applied water and the depth of water applied. The addition of the next irrigation water temporarily dilutes the soil water, but evapotranspiration concentrates it further. Some of the excess irrigation water percolates below the soil, dissolving salts from the subsoil on its way down towards the groundwater table.

Soil water is usually 2 to 3 times more concentrated than the applied irrigation water, and often 5 to 10 times. One objective of farmers in operating irrigation is to prevent levels of soil water mineralisation from reaching unacceptable levels in relation to the particular crops being grown. This is achieved by applying irrigation water in excess of crop requirements to leach the salts from the soil. However, this merely transfers the salinity problem from the soil zone down to the underlying groundwater, and the resulting excess infiltration causes the water table to rise beneath the irrigated land. As this new source of infiltration greatly exceeds the much lower recharge rates under natural conditions, the water table rises can be very rapid, and rates in excess of 1 to 2 m per year have been widely recorded in India, Pakistan, and in Mexico. Leakage losses below the irrigation canals also contribute to the overall increase in recharge and rises in groundwater levels can be most marked in their vicinity.

The resultant waterlogging itself contributes to further salinity degradation, either because the groundwater was already relatively saline, as in the lowest part of the Indus Valley, or because the rising groundwater dissolves more salts from the aquifer, from the subsoil and from the soil itself. Eventually, if the water table rises to within a metre or so of the land surface, direct evaporation from the aquifer will decrease the rate of rise but also further increase salinity.

Local factors may combine with the overall mechanisms outlined above to worsen the situation. The greatly increased infiltration when irrigation is initially applied may leach out salts already present in arid soils and subsoils. In the Lower Yaqui Valley in Mexico, for example, initial commissioning of land by applying an excessive irrigation of 1000 mm (equivalent to perhaps 10 years rainfall in one event) appears to have greatly increased the salinity of the underlying groundwater. In the Murray-Darling Basin of southern Australia, clearance of natural vegetation increased recharge and leaching of soil salts increased salinity in the underlying aquifer.

Particularly difficult problems are caused by soda salinisation from alkaline groundwaters or dilute, sodium-containing irrigation waters, as for example the Nile and Indus. In the most severe cases, the adsorption capacity is exceeded and the soils quickly become saturated with sodium, taking up to 70 per cent of the cation exchange capacity. Soil alkalinity rises to pH 9 to 11, causing a soil structure breakdown which reduces permeability, aeration, infiltration capacity and soil workability, as well as producing highly damaging soil compaction.

Thus, while the chemical and physical processes contributing to salinisation are sometimes complex, the root of the problem is clearly the introduction of excess irrigation water without adequate drainage measures. Waterlogging and salinity can result even if the applied surface water is of very good quality, and this fact is certainly not always appreciated. Salinisation will be quicker and more pronounced if the irrigation water is of poor initial quality, for example where groundwater of marginal quality, perhaps already affected by the mechanisms outlined above, is used or where waste water is reused to irrigate crops.

PREVENTING, CONTROLLING AND REVERSING SALINISATION

The prevention of waterlogging and salinity requires more efficient irrigated agriculture or effective

BOX 37 SALINISATION AND WATERLOGGING PROBLEMS IN THE INDUS VALLEY, PAKISTAN

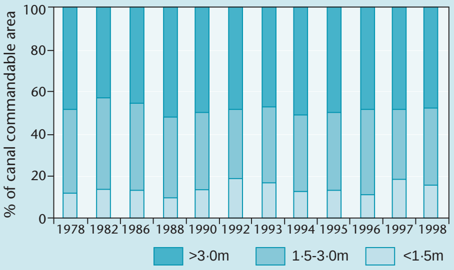
The Lower Indus Valley, shared between Pakistan and India, contains the largest contiguous irrigation system in the world, and was gradually developed over a period of some 60 to 70 years to the middle of the 20th century. The system eventually comprised 3 major reservoirs, 21 barrages or major headworks and 43 main canals. By the time these major delivery works were completed, the gross command area in the Lower Indus was 15.8 million ha, within which the area potentially irrigated—the cultivable command area—was about 14 million ha. The development of such a large irrigation system over land that was naturally arid (less than 200 mm/yr rainfall) was accompanied by a gradual rise in the water table, resulting from seepage losses from the huge network of unlined canals and from deep percolation from the irrigated fields. The obstruction of natural drainage by road and rail embankments and elevated canals in an area with low topographical gradients also contributed, by allowing impounded rainfall to become additional groundwater recharge.

In the upper part of the Indus Plain in Punjab, the water table under pre-irrigation conditions was about 30 m below ground. It subsequently rose by 0.3 to 0.9 m/yr so that by the mid-1950s it was within 1 to 2 m of the land surface over large parts of the irrigation system, and the resulting waterlogging and salinity had become a major national issue. A comprehensive survey at this time suggested just over 2 million ha were severely affected by salinity, 4.6 million ha moderately affected and some 4.8 million ha were waterlogged or poorly drained. Estimates in the late 1970s suggested 2 million ha of irrigated land had been abandoned as completely unproductive because of severe salinity and another 1 million ha had suffered severe deterioration. The economic cost of this loss of productive land is difficult to estimate, but in the early 1990s was put at between 10 and 20 billion rupees per year, and adversely affected the livelihoods of about 16 million people.

Although the need for improved drainage was recognised, for many years not enough was actually done to control waterlogging and salinity. Management options include drainage through groundwater abstraction, surface drains, subsurface tile drains, and conjunctive use of surface water and groundwater for irrigation. These measures have been incorporated into Salinity Control and Reclamation Projects (SCARPs). These started in the late 1950s in the middle Rechna Doab in Punjab and gradually spread over the next 25 years to other affected areas. In total, some 25 000 boreholes were put into operation, and tile drainage has been provided to 0.4 million ha of the finer grained sediments in Sindh, towards the southern end of the irrigated area, at a total cost of perhaps 90 billion rupees. Where the abstracted groundwater is of low enough salinity, it is used directly for irrigation or put back into the canal system, but it is necessary to dispose of the large volumes of saline water, especially in the southern part of the system. To achieve this, a network of collector drains carries the saline water to the Left Bank Outfall Drain (LBOD) and thence to the sea, a major, costly engineering project which still only removes about 25 per cent of the salt load from the Lower Indus system.

Improvement in soil quality by SCARPS (from IWASRI, 1995)

SCARP No.	Survey Period	% profiles by salinity classes			
		Normal	Saline	Saline-sodic	Sodic
I	1962-63	36.6	13.9	44.1	5.4
	1977-80	71.4	9.2	17.4	2.0
II	1962-65	58.0	9.0	25.0	8.0
	1977-80	78.0	8.0	10.0	4.0
III	1962-63	49.0	6.0	38.0	7.0
	1977-80	71.1	6.2	16.5	6.2
IV	1962-65	25.0	28.0	46.0	1.0
	1977-80	62.6	16.2	20.2	1.0



Waterlogging control trends in the Lower Indus Valley irrigated area (from Bhutta and Chaudhry, 1999).

As shown above, careful monitoring of groundwater levels and soil salinity in the SCARPs suggests the situation has not got worse overall and there has been some success in controlling groundwater levels and in restoring saline soils. However, the operating costs have proved to be an enormous burden, and poor construction/maintenance, weak institutional capacity and lack of involvement of the farmers themselves have combined to make the SCARP groundwater pumping significantly less than the design expectation. Finally, at the macro scale, eventual disposal of the salt load, rather than cycling it within the system, remains a very difficult objective to achieve.

BOX 38 OTHER SALINISATION THREATS TO GROUNDWATER

Apart from the build up in irrigated areas of salts in agricultural soils and their subsequent leaching to underlying aquifers, salinisation of aquifers can occur for other reasons. There are numerous possible salinity sources, some of which may be extensive and others very localised. Where groundwater in island, coastal or inland basin aquifers is affected, salinity problems may be complex and come from more than one source but it is important to distinguish the real reason(s) for encountering saline groundwater for an appropriate management response to control the problem. This can be achieved only by a clear understanding of aquifer behaviour (from a groundwater resource and hydrochemical study) based on reliable and representative monitoring data.

Potential sources of salinity in coastal and inland basin aquifer (modified from Custodio, 2002)

Salinity source	Potential impact	Comments on examples
Encroachment of modern seawater	Extensive	Commonly assumed to be the mechanism for salinisation trends in coastal boreholes, but may not be the case in some geological settings
Unflushed old marine water in very slow flow aquifers or in aquitards	Extensive	Global sea levels varied between glacial and interglacial periods by more than 100 m during the last 2.6 million years. Affects lowland aquifers receiving limited recharge that is insufficient for flushing
Sea-water spray in windy coastal strips	Variable	Can be a significant problem in small, low-lying oceanic islands
Intensive evaporation of outflowing groundwater in discharge areas and wetlands	Variable	Inland drainage saltpans and coastal sabkhas may be a source of wind-blown salt deposited as aerosol on downwind areas; an extreme example is the Aral Sea
Dissolution of evaporite salt in the strata or in near-surface structures in geological formations	Variable	Extent not documented
Displacement of saline groundwater contained in some deep formations	Limited	Up-coning in coastal/island situations due to overpumping but also inland, from deep brackish water dewatered for mining purposes from old formations, for example former coal mines in England
Pollution by saline water derived from industrial/mining activities	Limited	Mine drainage and tip leaching, especially in salt and potash mines but also in some coal mines
	Limited	Leakage from industrial processes and cooling facilities using brackish or saline water
	Limited	Effluents from softening, de-ionisation and desalination plans
	Variable	Infiltration of discarded oilfield brines, especially from earlier production phases
	Extensive	Dissolution of de-icing road salt
	Limited	Intense evaporation of water in factories and disposal of waste water on site
Brackish water imported from other areas	Variable	Long arid-zone rivers receiving irrigation drainage returns or subject to high evaporation and in hydraulic continuity with downstream lowland aquifers
Infiltration of saline return irrigation flows	Extensive	Especially if irrigation water has quality constraints, for example from urban waste water reuse
Intense evapo-concentration of surface and phreatic water in dry climates	Extensive	See section on salinisation in this chapter

Extensive	*Could have major impact on resource if allowed to affect large areas, thicknesses or volumes of aquifer*
Limited	*Effects may be serious locally but are likely to be of limited overall impact on the resource unless the aquifer is small/thin or the magnitude/duration of contaminant load source is uncommonly large*
Variable	*Impact dependent on local setting and conditions*

drainage measures, or better still a combination of the two. Improved efficiency of water use has been the subject of much research by irrigation engineers and agronomists, and many techniques are now employed, of varying technical complexity and cost. The least sophisticated improvements to traditional furrow and basin systems such as proper land levelling and better control of water distribution and application can have dramatic benefits. Reducing the difference in level between the top and bottom of a farmer's irrigation furrows by only a few centimetres can reduce his water use by up to 40 per cent. Laser-controlled land levelling in the United States has enabled irrigators using gravity applications to achieve up to 90 per cent efficiency.

In many places, traditional furrow and basin irrigation is being replaced by sprinklers, drip and trickle micro-irrigation techniques. Centre pivot sprinklers can increase efficiency by up to 70 per cent and micro-irrigation techniques by an additional 20 to 25 per cent. The most recent developments in precision application have been able to achieve 99 per cent efficiency from mobile drip units that move slowly through the field to discharge small volumes of water right beside the plants. There is, however, still some way to go before the potential efficiencies are reliably achieved. Although the more sophisticated techniques are inherently more efficient, the wide range of result actually achieved shows that, as for all systems, management is a key factor, and technical problems remain. The effectiveness of sprinkler systems suffers in very high winds, and trickle systems can be badly affected by clogging, making them unsuitable for reuse of waste water or even for waters with only moderate dissolved solids. Nevertheless, improved irrigation efficiency is attractive because it can reduce the volume of water required and hence offer scope for extending the area under irrigation without the need for additional water.

Adequate drainage of irrigated land to prevent or reduce waterlogging requires a general lowering of the water table to 2 to 3 m below ground. This can be achieved by open ditches, tile drains or pumping from boreholes, and the choice depends on the permeabilities of the soil, subsoil and underlying aquifer material, on the funds available for the capital works, on the resources of local communities for operation and maintenance and the energy costs of pumping. The experience of the major salinity control programmes in Pakistan, where over a quarter of irrigated land is affected, is summarised in Box 37.

OTHER SALINITY PROBLEMS - A MAJOR GROUNDWATER QUALITY THREAT

Finally, it is as well to remember that salinisation due to irrigation mismanagement is only one of a number of salinity problems that affect global groundwater resources (Box 38). Water quality can be degraded from salinity of various origins and the results are ubiquitous in all groundwater settings and aquifer types; both islands and continents, on coastal areas and inland basins, in temperate climates and arid, in urban or rural settings, beneath agricultural or industrial activities, salinisation can provide a serious threat to sustainability if it is not managed with urgency and with commitment. It is not an exaggeration to identify salinity as globally the most widespread groundwater quality threat.

PROBLEMS FROM FERTILISERS

FERTILISER USE AND TRENDS

The highest rates of increase in nitrogen fertiliser use, during recent years, have been observed in the developing countries (Figure 21) where rates have tripled since 1975 and large increases in food production have resulted.

In Asia for example, a quarter of the growth in rice production has been attributed to increased fertiliser use. In Central and South American and South Asian regions, rates of application of nitrogen fertiliser can be high because with the aid of irrigation in favourable climatic conditions up to three crops a year can be raised.

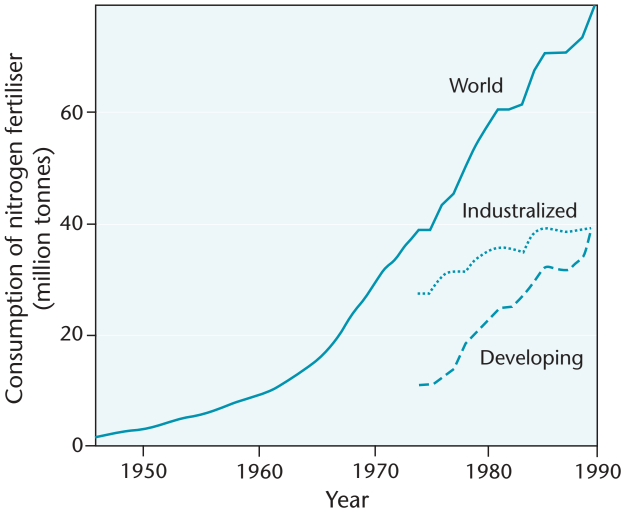


Figure 21. Consumption of nitrogen fertiliser, 1946-1989.

In future, it will not be possible to meet increased food demand by an increase in cropped area, since additional land suitable for cultivation will become scarce as a result of both land degradation and pressure from urban expansion. Neither is the area under irrigation likely to increase significantly, because water resources will either not be available or be needed for higher value uses such as urban and industrial supply. Increased food production can only realistically be achieved by a combination of better crop-water management, improved cultivation technique and increased intensification. Further expansion in artificial fertiliser application is likely to be a consequence of this process.

The principal nutrients provided by artificial fertilisers are nitrogen, phosphorus and potassium. Whilst nitrate is the principle nutrient leached from the soil, the widespread use of muriate of potash (KCl) as a source of potassium in many countries can cause a build-up of groundwater chloride concentrations. The presence of high potassium and phosphate in groundwater has been only infrequently reported. This is in part attributed to the lower application rates in typical arable fertiliser mixes and also, especially in the case of phosphate, to adsorption onto clays, both of which reduce the effective rate leached to the water table.

EVALUATING RISK TO GROUNDWATER FROM EXCESS FERTILISER APPLICATION

The risk to groundwater depends on both the vulnerability of the aquifer and the nitrogen loading. Aquifer vulnerability, as described in Chapter 4, will depend on the relative ease and speed that contaminants can migrate from the soil zone to the water table. Thus areas underlain by thin permeable soils and a permeable aquifer with a shallow water table will be especially vulnerable to rapid increases in groundwater nitrate concentration. Extreme vulnerabilities are associated with fractured formations. Nevertheless, as nitrate is highly soluble and not readily degraded under aerobic conditions, even less vulnerable aquifers will eventually be contaminated by excess nitrate, and only control of the loading will, eventually, reduce pollution to acceptable levels.

The nitrogen loading will be greatest where cultivation is intensive and double- or triple-cropping is practised (Boxes 39; 40). Especially high nitrogen leaching from soils can occur where irrigation is excessive and not carefully controlled.

BOX 39 INFLUENCE OF AGRICULTURE ON GROUNDWATER QUALITY IN THE CANARY ISLANDS

Agriculture is important in the Canary Islands and the main crops are grown for export under intensive irrigation in the low altitude coastal areas. At higher elevations (300 to 1000 m), more traditional cropping for local consumption is practised and these crops are less intensively irrigated (Figure A).

Gran Canaria is the third largest in size and the most heavily populated of the islands. Highest concentrations of nitrate in groundwater are observed in the coastal areas. Three distinct populations of nitrate concentrations can be seen, a low-nitrate background concentration, a higher nitrate peaking at 70 to 90 mg NO_3/l associated with agriculture, and a higher peak of up to 170 mg/l, corresponding to intense pollution where bananas are grown (Figure B).

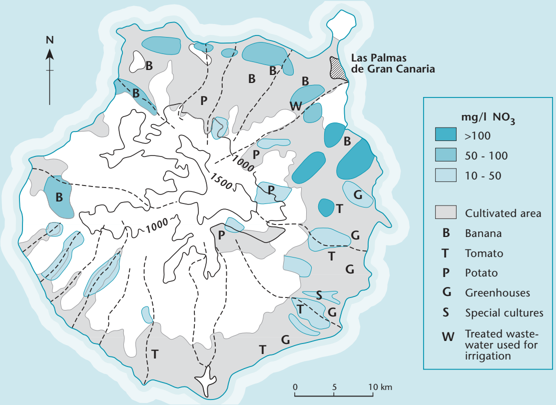


Figure A. Distribution of groundwater nitrate on Gran Canaria Island (after Custodio et al., 1984).

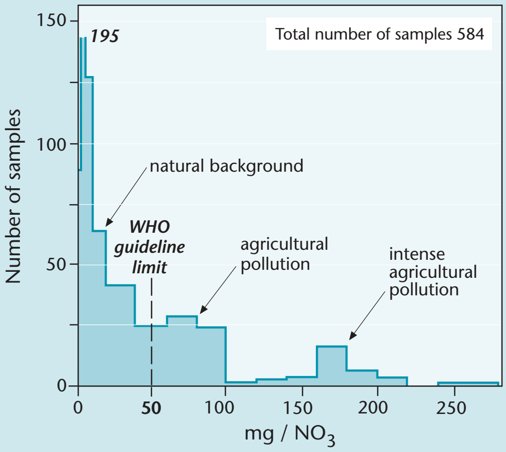
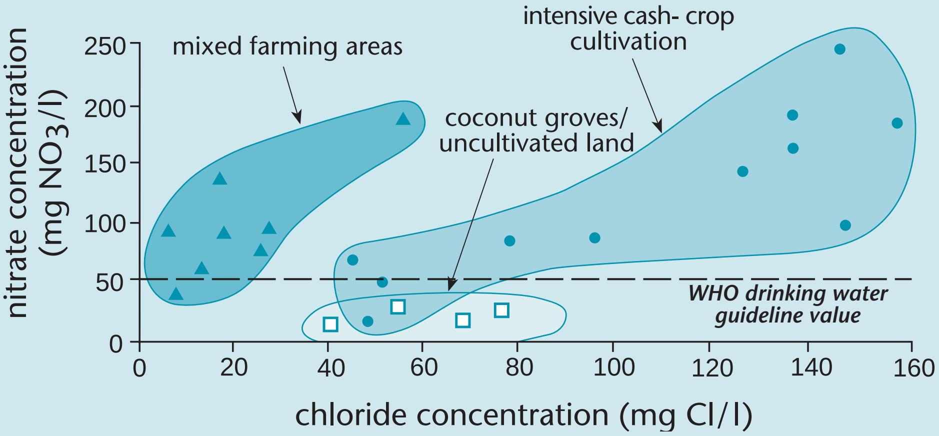


Figure B. Distribution of nitrate concentration of samples from deep large diameter dug wells on Gran Canaria Island (after Custodio et al., 1984).

BOX 40 NITRATE LEACHING BELOW INTENSIVELY CULTIVATED SOILS: TWO EXAMPLES FROM SRI LANKA

High groundwater nitrate concentrations have been recorded in the shallow limestone aquifer beneath the Jaffna peninsula in Sri Lanka. In a survey carried out in 1982, three-quarters of the wells sampled had concentrations in excess of the WHO recommended guideline value of 50 mg/l nitrate and some were in excess of 175 mg/l nitrate. In general, the highest concentrations were associated with wells located in intensively cropped areas where 2 to 3 crops of vegetables and tobacco were raised each year. Most domestic wells had low nitrate concentrations. The use of large quantities of inorganic fertilisers and manure together with excessive (flood) irrigation were considered to be responsible for the high nitrate content (Nagarajah et al., 1988). Conversely, nitrogen-leaching losses from the soil were low for traditional, rain-fed crops supported by low applications of fertiliser.

A similar pattern was observed in a study of the Kalpitiya Peninsula on Sri Lanka's western coast, double- and triple-cropping of onion and chillies were undertaken, with heavy nitrogenous fertiliser applications on permeable sandy soils overlying a sand aquifer. The diagram shows a good correspondence between groundwater nitrate concentration and land use, the correlation being maintained because abstraction from the irrigation wells helps restrict flow to localised 'cells' which represent very local recharge through the different cultivation types.



Relationship between groundwater nitrate concentrations and different agricultural land uses, Kalpitiya Peninsula, Sri Lanka (from Mubarak et al.,1992).

Thus knowledge of aquifer vulnerability, land-use/cropping patterns and typical application rates makes it relatively simple to identify areas where groundwater will be at risk from diffuse nitrate pollution. However two further factors need to be considered. Firstly, although nitrate is mobile and unlikely to degrade in aerobic environments, the process of denitrification can remove it. This occurs in poorly drained and anaerobic conditions, such as occur widely beneath many paddy (rice) cultivated areas. It is thought that this is why nitrate concentrations in groundwater beneath paddy are often low even when high applications of nitrogenous fertilisers are made. Secondly, climatic regime, or more precisely, the amount of annual recharge from precipitation will influence the amount of nitrate in groundwater through dilution effects, so that in semi-arid or arid regions nitrate concentrations will be proportionately greater than for an equivalent environment in a humid region.

OTHER SOURCES OF NITROGEN

Whilst high nitrate concentrations in groundwater have been widely reported and the leaching of fertiliser nitrogen has in many cases been suggested as the possible cause, it is important to recognise that other sources of groundwater nitrate exist. These include:

- geological sources, as in the saltpetre deposits of northern Chile;
- naturally high baseline concentrations in semi-arid areas, thought to be derived from nitrogen fixing vegetation such as acacia *species*. Affected waters in the Sahara/Sahel region of North Africa include

BOX 41 INFLUENCE OF CLIMATE ON GROUNDWATER NITRATE

A study was undertaken to compare nitrogen leaching losses from the soil and the nitrate concentration in the underlying groundwater in three different areas (East Botswana, southern India and south-west Sweden). Rates of nitrogen leaching from the soil in both southern India and Botswana were low, 2 to 3 and 1 to 2 kg N/ha respectively, and compared with 25 kg N/ha observed in south-west Sweden.

Annual flux of nitrogen calculated from studies in contrasting climatic regimes (from Lagerstedt et al., 1994)

Area	Pptn* (mm)	Fertilizer (kg/ha)	Animal manure (kg/ha)	N fixation (kg/ha)	Leaching (kg/ha)	Groundwater nitrate (mg/1)NO_3
E Botswana	500	0	33	15	1-2	33
S India	600	20	32	10-20	2-3	40
SW Sweden	800	100	33	Small	25	40-60

Pptn precipitation (rainfall, snowfall)

Despite the low nitrogen losses observed in both southern India and eastern Botswana, groundwater nitrate concentrations were comparable to those in south-west Sweden and this was attributed to low rates of infiltration, which permitted only limited dilution.

It is clear that semi-arid regions are very susceptible to nitrate pollution even from relatively low nitrate loadings and this has implications when planning development (e.g. increasing on-site sanitation coverage, improved agriculture etc.)

Further, in semi-arid regions even small changes in precipitation can have a disproportionate impact on recharge so that considerable fluctuations in groundwater nitrate concentration can be anticipated in response to changes in patterns of rainfall. These may become more widespread in response to global weather pattern changes.

those recharged thousands of years ago in the Pleistocene (‘palaeowaters’);

- irrigation with waste water downstream of urban areas;
- leachate from manure heaps, leaking slurry storage pits or livestock manure slurry spreading;
- unsewered sanitation;
- atmospheric deposition.

However, in rural areas, the most widely found non-agricultural source of nitrate is probably on-site sanitation systems and in rural communities where intensive agriculture and unsewered sanitation occur together, determining the relative contribution of each to the nitrate concentrations in groundwater is not easy.

In areas where intensive stock rearing is practiced, the accumulation of animal faeces around stock watering boreholes or wells can produce locally very high nitrate concentrations.

PROBLEMS FROM PESTICIDES

All pesticides are, from a chemical point of view, designed to be sufficiently toxic and persistent to control the weed, insect or fungal pest they are designed to deal with. Prior to the 1980s, there was relatively little concern that groundwater could be polluted by pesticides, because agricultural scientists suggested that the high molecular weight compounds, such as chlorinated hydrocarbon insecticides, would be strongly attenuated by sorption in the soil and the lower molecular weight compounds would be lost by volatilisation. However, advances in the understanding of the processes responsible for the widespread increase in nitrate concentrations in groundwater, referred to above, led naturally to a consideration of the risk to groundwater from pesticide use. If nitrate could be readily leached from agricultural land to the underlying groundwater, then it seemed likely that, with intensification of pesticide use, some of the more mobile pesticide compounds could be leached too.

While the potential for pesticide leaching was recognised, research into their fate and behaviour in the subsurface has been hampered by the high cost and technical sophistication of the analyses required to achieve the detection limits related to the drinking water standards and guideline values established by the EC, WHO and US EPA. The establishment of routine sampling and monitoring programmes is also made difficult by the wide range of compounds in common agricultural use, the low concentration threshold and the care required in sampling to avoid cross-contamination or volatile loss. Although analysis is indeed difficult and expensive, as described below pesticides have begun to be detected in groundwaters, and concern about leaching of these agricultural products from soils was well founded.

PESTICIDE USE

The largest individual consumer of pesticides is the United States, followed by the countries of Western Europe. Japan is the most intensive user of pesticides per unit area of cultivated land. Although developing countries together consume only a small proportion of the total, rates of increase in pesticide use are now greater in some of the more rapidly developing economies than in the developed world. Herbicides dominate in temperate climates in Europe and North America, but insecticides are more widely used elsewhere. Globally, pesticide use is concentrated on a small number of crops, more than 50 per cent of the total being applied to wheat, maize, cotton and soya bean. In developing countries, the highest applications are to plantation crops such as sugarcane, coffee, cocoa, pineapple, bananas and oil palm, although use on vegetables is becoming more important. Application rates are generally in the range 0.2 to 10 kg/ha/a of active ingredient, with the highest rates often for vegetables. This compares with fertiliser applications of several hundred kg/ha/a to temperate arable crops and improved pasture. Total consumption of pesticides continues to grow at around 3 to 4 per cent per year, the spread of pesticide use to new areas more than offsetting the tendency for new pesticide compounds to be effective at much lower dose rates.

OCCURRENCE OF PESTICIDES IN GROUNDWATER

Increasing numbers of pesticides are being detected in groundwater in Europe and North America as routine monitoring programmes are developed in response to tightening drinking water quality standards (Table 29). The EC Drinking Water Directive sets a very stringent maximum admissible

Table 29 Summary of pesticide use and occurrences in groundwater

Region	Dominant pesticide use	Typical compounds detected
United Kingdom	Pre- and post-emergent herbicides on cereals, triazine herbicides on maize and in orchards	Isoproturon, mecoprop, atrazine, simazine
Northern Europe	Cereal herbicides and triazines as above	As above
Southern Europe	Carbamate and chloropropane soil insecticides for soft fruit, triazines for maize	Atrazine, alachlor
Northern USA	Triazines on maize and carbamates on vegetables eg potatoes	Atrazine, aldicarb, metolachlor, alachlor and their metabolites
Southern & Western USA	On citrus and horticulture, and fumigants for fruit and crop storage	Aldicarb, alachlor and their metabolites, ethylene dibromide,
Central America & Caribbean	Fungicides for bananas, triazines for sugarcane, insecticides for cotton, and other plantation crops	Atrazine
South Asia	Organo-phosphorous & organo-chlorine insecticides in wide range of crops	Carbofuran, aldicarb, lindane,
Africa	Insect control in houses and for disease vectors	Little monitoring as yet

concentration of 0.1 µg/l for any pesticide, whereas WHO guidelines and US EPA maximum contaminant levels are derived from individual toxicity-based assessments of each compound.

Most routine monitoring programmes or major surveys report results in which a substantial number or even the majority of samples have pesticide detections below the limits of detection, and the bulk of the positive detections are in the same general range as standards or guideline values (0.1 to 10 µg/l). Concentrations significantly above this range are likely to indicate point source pollution rather than normal agricultural use. Common activities producing such pollution include:

- non-agricultural, amenity use of general weedkillers;
- poor practice in pesticide storage or disposal of pesticide spray tank washings, sheep dip and other livestock chemicals into the subsurface;
- landfill disposal of pesticide processing wastes.

Non-agricultural use of pesticides, for example to keep railways, highways, airfields, car parks and other paved areas free of weeds, causes widespread problems in Europe, especially where the drainage from such surfaces is via soakaways into the ground. This can be a rapid pollutant pathway to the underlying groundwater because it allows little time for attenuation by degradation or adsorption. In tropical countries, non-agricultural pesticide use includes insect control in and around houses, and spraying to control insect vectors for human diseases such as malaria. This often involves the application of those organochlorines whose use has been banned due to the adverse environmental effects resulting from their high persistence and extreme toxicity.

PESTICIDE FATE AND BEHAVIOUR

The natural processes that govern the fate and transport of pesticides in the soil can be grouped into the broad categories of sorption, leaching, volatilisation, degradation and plant uptake. Plant uptake is usually a small component. The way in which the pesticides are applied and act is important. The more mobile are those targeted at weeds and soil insects and applied to the soil, often before the crop emerges or is even sown. These are more likely to be leached than those sprayed on the plants and acting on the leaves/leaf pests. Many pesticide compounds are strongly sorbed onto the plants or on to clay particles and organic matter in the soil. Volatile losses can occur from the leaf surface, from the soil particles and from soil moisture. Pesticide compounds degrade in the soil by microbial and/or chemical processes to produce intermediate breakdown products known as metabolites and ultimately to simple compounds such as ammonia and carbon dioxide. Pesticide persistence in the soil, as defined by the half-life—the time for half of the mass of compound to be degraded—is measured by the manufacturers as part of the product registration process, and for the most mobile pesticides ranges from a few days to a few tens of days.

Of the attenuation processes included in Table 10, sorption, volatilisation and degradation are particularly important for pesticides and, as shown in the table, are most active in the soil zone with its high content of clay and organic matter and active microbial populations. While it can be expected that the small quantity of pesticide residues that pass below the active soil zone will be more mobile and persistent, nevertheless some degree of continuing sorption and degradation can be expected while pesticides are moving slowly to the water table. Once in the saturated zone, dilution will be the main attenuation mechanism to help limit even further the concentrations arriving at groundwater abstraction points.

The hydraulic characteristics of some aquifer types, particularly fractured formations, are such as to promote more rapid preferential groundwater movement which would allow much less time for sorption and degradation to occur. The outcome of these complications is that both field and laboratory studies are required to quantify the factors that control pesticide fate and behaviour in specific conditions and to provide this three-dimensional picture. Such studies are technically complex, logistically difficult and expensive to undertake, so there are as yet few detailed published examples. Simpler risk-based assessments or modelling approaches have had to be adopted instead (Box 42).

EVALUATING PESTICIDE POLLUTION HAZARDS

To thoroughly evaluate the current situation with regard to pesticides in groundwater, and to justify any required controls on pesticide use to protect drinking water supplies, knowledge of the contaminant load and the three-dimensional sub-surface distribution of pesticides beneath recharge areas is required. This is, however, easier said than done. Published data for sorption and persistence may refer only to standard,

BOX 42 RISK OF LEACHING OF PESTICIDES AND THEIR DERIVATIVES FROM TROPICAL AGRICULTURAL SOILS: EXAMPLES FROM BARBADOS, SRI LANKA AND INDIA

Research was undertaken to assess the fate of pesticide residues in the vulnerable limestone aquifer of Barbados. There the herbicides atrazine and ametryn are applied widely to sugarcane at rates of around 4 kg (active ingredient)/ha/a. Atrazine, and its derivative (metabolite) deethylated-atrazine, were regularly detected in groundwater at concentrations in the range of 0.5 to 3.0 µg/l and 0.2 to 2.0 µg/l respectively (Figure A).

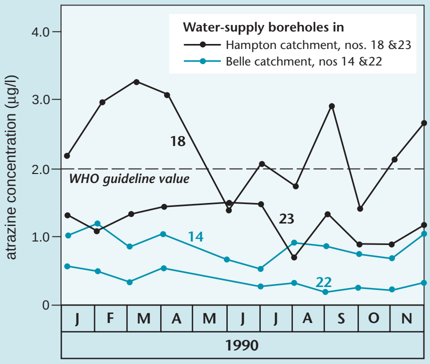


Figure A Groundwater atrazine concentrations in Barbados catchments under sugercane cultivation (from Wood and Chilton, 1995)

Other research conducted on the north-western coast of Sri Lanka and in India on the pesticide carbofuran has shown that the derivatives (metabolites) of some pesticides are also a contaminant class of concern to groundwater. The parent compound carbofuran, which was applied at 6 kg/ha (active ingredient)/ha to horticultural crops, is highly mobile. It was rapidly leached from the soil with concentrations of 200 to 2000 µg/1 in the soil drainage of a lysimeter and peak concentrations in excess of 50 µg/1 in the underlying shallow groundwater within 20 days of application (Figure B). The carbofuran was, however, subject to rapid degradation and in part transformed to its more persistent (but less mobile) metabolite, carbofuran-phenol. This remained in the shallow groundwater for more than 50 days. Results from a paddy field research site near Madras, India by Krishnasamy et al., 1993 support this picture of metabolite persistence. Monitoring of carbofuran residues in the soil confirmed that carbofuran phenol was the main metabolite and that it was retained in the soil layer for more than 80 days unlike the parent compound, which migrated rapidly but had largely disappeared within 15 days due to degradation.

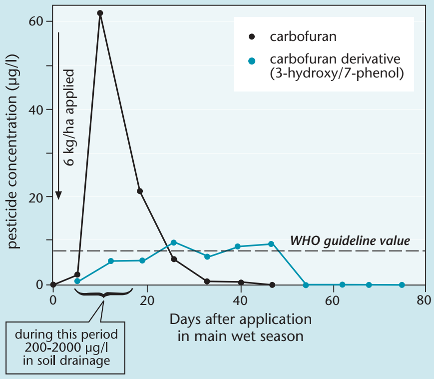


Figure B Leaching of the insecticide carbofuran from irrigated horticulture to shallow groundwater, Kalpitiya Peninsula, Sri Lanks (from Mubarak et al., 1992)

Although available research and monitoring is very sparse, there is sufficient to demonstrate that leaching of agricultural pesticide to shallow groundwater in highly vulnerable aquifers can be a hazard, and the potential persistence of toxic compounds in these systems is a risk. It is, however not possible to make a realistic assessment of the contamination risk to deeper groundwater in less vulnerable aquifers (Foster and Chilton, 1998). Given the wide range of pesticide compounds in use in agriculture, and their many toxic metabolites, an approach to groundwater pollution risk assessment based on the key properties of the pesticide compounds (mobility, solubility) and of the geological media (propensity to preferential flow in vadose zone) is needed to target monitoring.

In general terms, a significant additional element of protection for drinking water supplies will be provided if their intake is at significant depth below the water table, and the sanitary integrity of upper sections of the solid well casing is sound. This general aim is to provide additional aquifer residence time for pesticide degradation before entry to the water well concerned. Those wells most vulnerable to contamination by agricultural pesticides will be shallow dug wells providing domestic supplies to isolated rural farmsteads in areas of intensive cultivation.

temperate, fertile clay-rich and organic-rich soils in a temperate climate. There may be little or no such data for more permeable soils and for tropical conditions, and almost certainly none once below the soil zone for the broad range of aquifer materials types distinguished in Chapter 2.

Evaluating the potential for pesticides to pollute groundwater involves estimating which of the many compounds being used are most likely to be leached to groundwater, what are the most probable pathways, and what concentrations in groundwater could result. The concentrations and timing of pesticide residues arriving at the water table depend on the mass applied, antecedent weather conditions and application frequencies, the mobility and persistence of the compound and the hydrogeological conditions. Preliminary assessment of the transport of pesticides from soils to groundwater can be made from their physicochemical properties and a knowledge of groundwater flow characteristics, and various simple risk assessment methods based on the use of partition coefficients and half-lives have been developed. Recently an approach based purely on the size of the pesticide molecules has also been used to help assess whether pesticides will reach groundwater. These methods provide at best an indication of relative potential for leaching to groundwater, rather than predicting actual pesticide concentrations in specific subsurface environments. They can and should be used, as in the Barbados case in Box 42, to assist in selecting from the many pesticide compounds in use those which are most likely to be encountered in groundwater and therefore should be included in a groundwater quality survey or monitoring programme.

OTHER ISSUES AFFECTING RURAL AQUIFERS

ON-SITE SANITATION SYSTEMS AND GROUNDWATER POLLUTION RISK

The provision of sanitation facilities is an important public health measure that together with hygiene education contributes significantly to reduction in the disease burden of the population. Whilst the absence of water and sanitation facilities is associated with high rates of disease incidence and infant mortality rates, improvements in sanitation need to be integrated and properly planned, otherwise one unanticipated outcome may be the contamination of drinking water by faecal matter derived from on-site sanitation.

On-site sanitation systems, which include septic tanks and all forms of pit latrine, store wastes at the point of disposal. These wastes usually undergo some degree of decomposition on site, but even so, on-site systems require either periodic emptying or construction of new facilities once they fill up. Septic tanks typically hold the solids compartment of wastes in a sealed tank where the matter decomposes anaerobically; the liquid effluent is usually discharged into a soakaway. Pit latrines are generally not sealed and are usually only appropriate where the level of water supply is low (communal or yard) and minimal liquid volumes are generated.

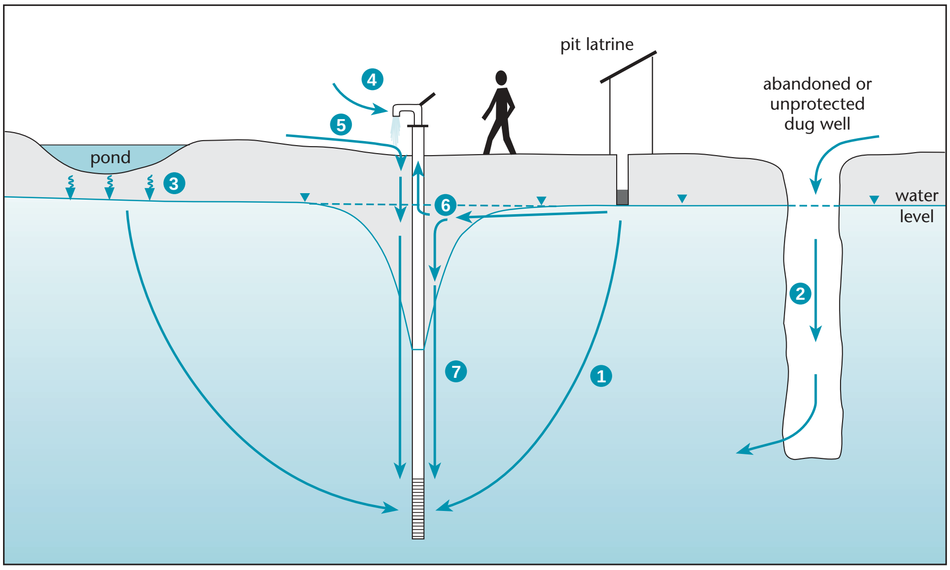
Sanitation coverage varies widely both between different regions of the world and, within a country, between urban and rural populations. It is estimated that globally two billion people do not have adequate sanitation, and coverage in rural areas, especially in parts of Africa, can be very low. To meet global development targets, improvements in water supply and sanitation are likely to focus on increasing sanitation coverage, and assessing the pollution risk to groundwater posed by on-site sanitation system is likely to become more important. The principal hazard from on-site sanitation is the risk of transmission of pathogenic micro-organisms. Concentrations of nitrate in excess of the WHO guideline limit can give rise to methaemoglobinaemia (or blue-baby syndrome).

Microbiological Hazard
Contamination of groundwater supplies by micro-organisms where on-site sanitation systems are employed can occur via two pathways (Figure 22):

i Indirect localised pathway that develops because of the poor design and/or construction of the water supply and its headworks. This pathway provides a rapid bypass mechanism from the surface to the intake of the supply for water contaminated by various means around the wellhead. This limits the residence time of the microbes in the subsurface, removing opportunity for attenuation through die-off and predation.

ii Direct aquifer pathway, where pathogens migrate through the subsoil from the base of the latrine to the water table and from there to the intake of the well or screen.

The former pathway is a common route for well contamination by micro-organisms although it can be relatively easily prevented by correct design of water



Aquifer pollution pathways

Pathways direct from pit latrine

① Deep penetration through strata

② Contamination via abandoned/unprotected dug well

③ Infiltration from a contaminated surface water body

Localised/indirect pathways

④ Direct contamination of spout (by dirty hands)

⑤ Surface water seepage behind tubewell casing

⑥ Lateral migration at water table and entry through defective casing

⑦ Lateral migration at water table and percolation behind the casing to the screen

Figure 22. Pathways for pollution of groundwater supplies by on-site sanitation.

supply/headworks, competent construction and careful attention to simple maintenance requirements. Minimising the hazard from the latter pathway relies on the long-recognized ability of the subsurface to purify water through the natural processes of attenuation.

The mechanisms controlling the attenuation of micro-organisms are complex and field research evidence suggests survival and breakthrough are variable, being dependent on local conditions and season. Increased breakthrough following rainfall is widely recorded. Such variability makes it difficult to have complete confidence in arbitrary separation distances between contaminant source and groundwater supply.

Empirical evidence from a limited number of field studies has shown that a time separation between the pollution source and the water supply equivalent to 25 days travel time is usually sufficient to reduce concentrations of faecal indicators (bacteria such as E.coli or thermotolerant coliforms used as pointers to recent faecal contamination) to levels where detection within most samples is unlikely. However, the studies did not analyse for other pathogens such as viruses that may survive for longer periods in the subsurface.

The generally accepted minimum time separation for contaminant source and groundwater supply in western Europe, which aims to bring water quality within WHO guidelines or national standards, is equivalent to 50 days travel time through the saturated zone. This is based on survival times of viruses from laboratory and field experiments. One practical problem in applying this travel time to communities employing on-site sanitation in the developing world is that it may result in prohibitively large separation distances in certain geological settings. A manual* developed to provide practical guidance on safe design of local water supply and sanitation systems proposed that the hazard posed by different systems could be assessed at three levels of risk.

- Significant risk – less than 25 day travel time;
- Low risk – between 25 and 50 day travel time;
- Very low risk – greater than 50 day travel time.

Minimizing microbiological hazard to rural groundwater supplies

The microbiological quality of water from rural boreholes, dug wells and springs will be at risk where:

- the design and construction of a groundwater supply is defective, especially if headworks sanitary protection measures are inadequate;
- headworks sanitary measures are not maintained and potentially contaminating activities occur in the vicinity of the headworks.

Good design and construction of groundwater abstractions (boreholes, wells, springs) is critical to the prevention of pollution, and key criteria include:

- maximising the residence time for water tapped by

Table 30 Examples of improved sanitary protection measures for different groundwater sources

Type	General measures	Specific sanitary completion measures
Borehole	Well-head protection to prevent direct contamination	apron extends at least 1.5m from casing/lining
		no cracks in apron
		no ponding of water on the apron
		the join between apron and the casing/lining is sound
		the sanitary seal (grouting, clay fill) surrounding the lining below ground level has been competently installed
	Immediate area managed properly	the floor is sloped away from the well head
		fencing excludes animals from the well head
		diversion ditches direct run-off away from the well head
		ponding of surface water close to borehole does not occur
Protected spring	Protection works to prevent direct contamination	backfill area behind a spring box or retaining wall protected and retains grass cover
		retaining wall and other protection works kept in good order
		fencing excludes animals from the backfill area
	Immediate area managed properly	diversion ditches direct run-off away from the backfill area
		good drainage of waste water from spring
		ponding of surface water uphill and close to spring does not occur
Dug well	Well-head protection to prevent direct contamination	apron around well head extends at least 1.5 m
		well head raised by at least 0.3 m and covered by slab
		no cracks in apron
		no pounding of water on the apron
		join between apron and the casing/lining is sound
		floor is sloped away from the well head
		hand pump or windlass and dedicated bucket used to withdraw water
	Immediate area managed properly	fencing excludes animals from the well head
		diversion ditches direct run-off away from the well head
		ponding of surface water close to well does not occur

the borehole, well or spring, because it must be assumed that a proportion of the supply may contain water travelling from the base of the pit latrine to the water table and from there to the water supply. This travel time should exceed 25 days and where practical, exceed 50 days. The usual design response is to make well/borehole intakes deeper or increase the separation between the water supply and the pit latrine. The former solution is preferred because it is often the more practical option where space is limited and because lateral rates of water movement laterally can vary, especially where the aquifer is layered. However where aquifers are thin or where dug wells are the preferred water supply option then proving a 'safe' horizontal separation will be critical;

- improving the sanitary protection measures at the headworks of the water supply to limit the likelihood of localised pollution. These measures should aim to minimize pathways that may develop as a result of the construction of the water source, keep sources of contamination as far away from the water supply as feasible and be as maintenance-free as practicable.

Tables 30 and 31 summarise specific factors, but for more details on both aspects, the reader is referred to the ARGOSS manual.*

Hazard from nitrate

The most mobile contaminants from on-site sanitation are nitrate and chloride. A person excretes in the region of 4 kg of nitrogen and about 2 kg of chloride per year, and under aerobic conditions it can be expected that a significant percentage of organic

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* ARGOSS 2001. Guidelines for assessing risk to groundwater from on-site sanitation. *British Geological Survey Commissioned Report CR/01/142.* BGS Keyworth, and on the World Bank's website (Water Resources Management sector): http://lnweb18.worldbank.org/essd/essdext.nsf/18DocByUnid/98C34D734A6D82B085256B500068DEDC?Opendocument

Table 31 Examples of localised pathway factors for different groundwater sources

Type	Pathway factor	Contributing factors to pollution
Borehole	Gap between riser pipe and apron	Lack of diversion ditch Lack of waste-water drain Animal access to borehole, lack of fence
	Damaged apron	Lack of diversion ditch Lack of waste-water drain Animal access to borehole, lack of fence
Protected spring	Eroded backfill or loss of vegetation cover	Lack of uphill diversion ditch Lack of fence Animal access close to the spring
	Faulty masonry	Lack of uphill diversion ditch Lack of fence Animal access close to the spring
Dug well	Lack of headwall	Lack of diversion ditch Lack of waste-water drain Animal access to borehole, lack of fence
	Lack of cover	Animal access to borehole Uncontrolled use
	Use of bucket and rope	Various buckets used and removed from windlass Rope/bucket contacts ground surface if no windlass
	Gap between apron and well lining	Lack of diversion ditch Lack of waste-water drain Animal access to dug well
	Damaged apron	Lack of diversion ditch Lack of waste-water drain Animal access to dug well

nitrogen will be oxidized to form nitrate, which is mobile and not retarded. The nitrate nitrogen contaminant load can be assessed based on population density, rate of rainfall recharge and per capita water use if the proportion of excreted nitrogen which is leached can be estimated (the latter can be quite variable).

There are however processes which can mitigate the concentration of nitrate in some settings. In the saturated zone and where groundwater conditions are anaerobic, denitrification can occur. Denitrification is a microbiological process in which bacteria use nitrate (in the absence of oxygen) for their metabolic needs, producing nitrogen gas. Research in an urban low-income settlement in Dhaka, Bangladesh, showed that this mitigating process can also occur where dense population levels generate very high organic loads which consume all available oxygen. In the saturated zone, dilution is the other attenuation process that that can reduce nitrate concentration.

However, this will not be particularly effective where the nitrate load is high and derived from a large number of point sources over an extensive area (equivalent to widespread diffuse leaching of nitrate). In many cases, a nitrate front is developed that slowly migrates downwards from the surface through the groundwater. Once high levels of nitrate are present in groundwater, concentrations will not decrease rapidly, even if the load is reduced or removed.

WASTE WATER REUSE FOR AGRICULTURE

Potential for waste water reuse for agriculture

The very rapid urban growth of the last few decades described in Chapter 5 has produced increasing demands for potable water. As a result of this growth and the associated industrialisation, near-urban surface water resources typically become either fully utilised or of poor quality unless the city is located on a major river system. The improved sanitation coverage in large cities with water-borne sewerage systems produces enormous volumes of waste water for disposal. With the increasing scarcity of freshwater resources in arid and semi-arid regions, but ever-growing demand for more efficient food production for the expanding populations, much wider recognition is being given to waste water as an important resource. Waste water reuse is likely to become more widely practised, and it is already becoming incorporated into some national water resources management plans, and therefore will need to be taken account of in groundwater protection strategies.

The expanding demand for groundwater for potable supply and the desire to utilise waste water to conserve scarce freshwater often occur together, and waste water reuse can have major impacts on groundwater. In some situations, the substantial volumes of additional recharge may completely alter the local hydrogeology. Perched aquifers, new groundwater flow regimes and discharge points may be created. The impacts may be both positive for water conservation and negative in relation to groundwater quality. Improper disposal of untreated waste water directly into aquifers or use for irrigation at the ground surface above important aquifers can cause serious pollution problems. On the other hand, properly controlled and managed reuse can provide significant additional resources of good quality nutrient-rich water for arable agricultural purposes.

To illustrate the scope for waste-water irrigation, a city of 500 000 people each using 200 l/d would produce about 30 million m^3/year of waste water, assuming 85 per cent was collected by the municipal sewerage system. If the treated waste water were used at a reasonably efficient rate of 5000 m^3/ha/year, then some 6000 ha could be irrigated. Further, with typical nutrient concentrations of 50 mg/l N, 10 mg/l P and 30 mg/l K in waste water, all of the nitrogen and most of the phosphorus and potassium normally required for crop production would be supplied by the effluent. Thus, while the economic benefits of waste-water irrigation are clear, adequate knowledge of the hydrogeology, infiltration and recharge processes and the movement and natural attenuation of pollutants are required for effective design and management of waste-water irrigation systems.

Approaches to waste water reuse and irrigation

The methods employed to reuse waste water for irrigation vary considerably, depending on the volumes of water and areas of land available, the level of treatment employed, the types of crops to be irrigated, the level of technical capacity and investment of the farmers and environmental considerations. The typical, but probably not exhaustive range is shown in Table 31.

Thus, the scale ranges from localised, peri-urban, often informal irrigation of small gardens by collected but untreated waste water, with simple irrigation methods and few controls, to the large, canal commanded irrigation schemes of thousands of hectares, but still using untreated waste water, to highly sophisticated, heavily controlled and managed soil aquifer treatment in which the re-abstracted, fully

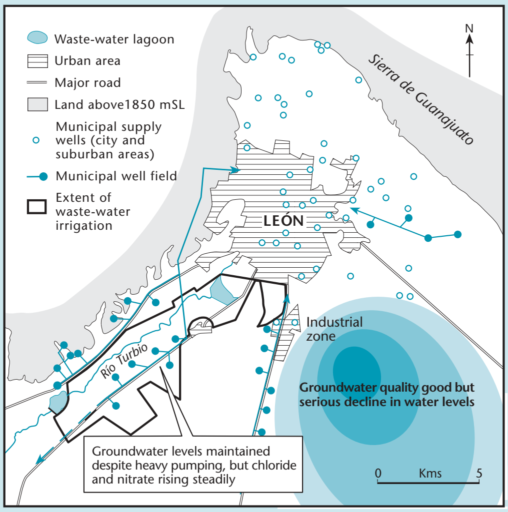
Table 32 Examples of waste-water irrigation approaches

Scale/type	Treatment level	Irrigation method	Crops	Example
Peri-urban gardens	Untreated	Basin, flood	Vegetables, fruit, fodder	Quetta, Baluchistan
Large canal schemes	Untreated	Basin, flood, furrow	Alfalfa, maize, wheat	León, Mezquital, Mexico
Horticulture and amenity woodland	Primary, stabilisation ponds	Furrow	Vegetables, trees	Lima, Perú
Horticulture	Primary, stabilisation ponds	Pumped from river containing effluent	Vegetables	As Samra, Jordan
Cattle pastures	Primary, lagoons,	Furrow and sprinkler	Natural grassland	Harare, Zimbabwe
Soil-aquifer treatment (SAT)	Secondary effluent infiltrated, SAT provides tertiary level	Subsequent abstraction of groundwater, use of sprinkler and other high-technology systems	Citrus fruit, vegetables	California, Dan Region, Israel

BOX 43 WASTE-WATER RE-USE FOR AGRICULTURAL IRRIGATION IN LEÓN-GUANAJUATO, CENTRAL MEXICO.

The city of León-Guanajuato (population 1.2 million) is one of the fastest growing cities in Mexico, and is highly dependent on groundwater for public supply. Groundwater is abstracted mainly from aquifers downstream of the city, including areas where waste water is used for agricultural irrigation. León's major leather processing and shoe manufacturing industry result in an urban waste water of relatively high salinity and chromium content.

A recent study (Foster, 1996; Chilton et al, 1998) showed that high rates of recharge from excess waste-water irrigation on alfalfa and maize south-west of the city (coupled with no agricultural abstraction) have helped maintain groundwater levels within 10 m depth, despite intensive abstraction from deeper horizons for municipal water supply. In adjacent areas water levels are falling at 2 to 5 m/a (see Figure).



Municipal water: supply and waste water re-use areas of León-Guanajuato, Mexico.

Mobile, persistent contaminants in the waste water Salinity problems are beginning to affect a number of production wells in the waste-water irrigation area. In the most seriously affected well, the chloride concentration rose from 100 mg/1 to 230 mg/1 in 2 years (even though the boreholes in this well field are screened from 200 to 400 m depth) and it is predicted that chloride content could rise to 400 mg/1 by 2010 in all the neighbouring wells if no remedial action is taken. There is also evidence of increasing nitrate concentrations.

Degradable contaminants in the waste water In contrast, no significant levels of pathogenic micro-organisms or faecal coliform indicators are found in the groundwater, and the organic carbon content reacts to produce high bicarbonate concentrations in groundwater. Also, although the waste water contains large concentrations of chromium salts, the chromium content of groundwater will remain low. Soil sampling has confirmed that both chromium and other heavy metals are accumulating in the soil, with very little passing below a depth of 0.3 m.

It is thus not necessarily the most toxic component of an effluent which poses the main threat to groundwater, and this example highlights the importance of understanding pollutant transport in the subsurface. Future management will need to address the problem of rising salinity, while continuing to reap the benefit from the advantages of reusing the waste water in agriculture.

treated effluent can be used to grow any type of crop using sophisticated and efficient irrigation techniques.

Protecting groundwater quality from waste-water irrigation—lessons from Mexico

Waste-water irrigation can pose direct health risks to the farmers and to the consumers of the crops grown, and can cause various quality deteriorations over time to the irrigated soils and to surface water and groundwater resources. The WHO Guidelines for Wastewater Reuse are intended primarily to help reduce the risks to workers and consumers from microbiological contaminants, rather than to protect the receiving surface waters or groundwater from deterioration in chemical quality. From the general characteristics of urban waste water summarised in Chapter 5, elevated concentrations of salinity, nutrients, organic carbon, pathogens and suspended solids can be expected. Where a significant industrial component of waste water exists, this will provide added pollutant concentrations that reflect the proportion of industrial effluents and the type of industries, such as heavy metals and specific industrial organic compounds such as the halogenated solvents. The case of León in Mexico, with its dominant tanning and leather goods industries, provides a good illustration of this, as described in Box 43.

Without going into great detail, it is clear that protecting the quality of surface waters and groundwater is intimately linked to the management and operation of both the waste-water collection and treatment facilities and the irrigation system. Thus, for systems using stabilisation ponds, adequate retention time is critical for the proper reduction in organic loading and faecal coliforms, and these can be severely compromised when the design organic and hydraulic loadings are exceeded, as became increasingly the case at As Samra in Jordan until additional capacity was recently constructed. Where reduction in nitrogen is a treatment objective before soil-aquifer treatment, as in the highly studied and monitored Flushing Meadows and 23rd Avenue sites at Phoenix, Arizona, adequate basin capacity to allow regular, in this case two-weekly, flooding and drying cycles is required.

In Mexico, irrigation with untreated waste water remains the norm, and the most suitable (commandable and irrigable) land close to the cities producing the waste water often overlies the aquifers providing part of the municipal supply. Some of these schemes, such as the one in the Mezquital Valley (which receives the waste water from the Mexico City conurbation) have grown gradually, extending to surround urban supply well fields. Protection of groundwater quality was not an important consideration until quite recently, and is clearly dependent more on the operation and management of the irrigation. Thus, studies of León and Mezquital concluded there was little scope with waste-water irrigation for improved efficiency to reduce the contaminant load, as higher technology application methods are vulnerable to clogging and the free availability of waste water in any case provides little incentive for more efficient use.

In Mezquital, retention of part of the waste water in dams and subsequent dilution with fresh surface water offers the prospect of some improvement in quality, but such augmentation with scarce additional freshwater resources would be very expensive. Exploitation of shallow, polluted groundwater for irrigation could intercept the downward transport of more mobile contaminants to protect deep public supply boreholes tapping underlying horizons. Though costly to construct and operate, this might allow less rigorous constraints on cropping and provide an opportunity to irrigate crops offering higher economic returns. Substitution of groundwater for surface water might also allow extension of waste water use, to irrigate additional land further downstream.

Protection zones may be required around individual supply boreholes to prevent direct ingress of waste water around the borehole and to lessen the possibility of downward movement of pollutants induced by heavy and continuous pumping close to individual boreholes or well fields. In the end, there may be no alternative to at least partial treatment, although in the case of Mezquital this might have the result that Mexico City would prefer to retain the waste water itself (as a resource) rather than export it to the neighbouring valley.

References
Bibliography (pp.120-125) numbers 8, 11, 14, 15, 16, 28, 30, 31, 38, 50, 52, 54, 58, 62, 72, 74, 75, 85, 87, 92, 94, 115, 116 and 120 have been used in the production of this chapter.