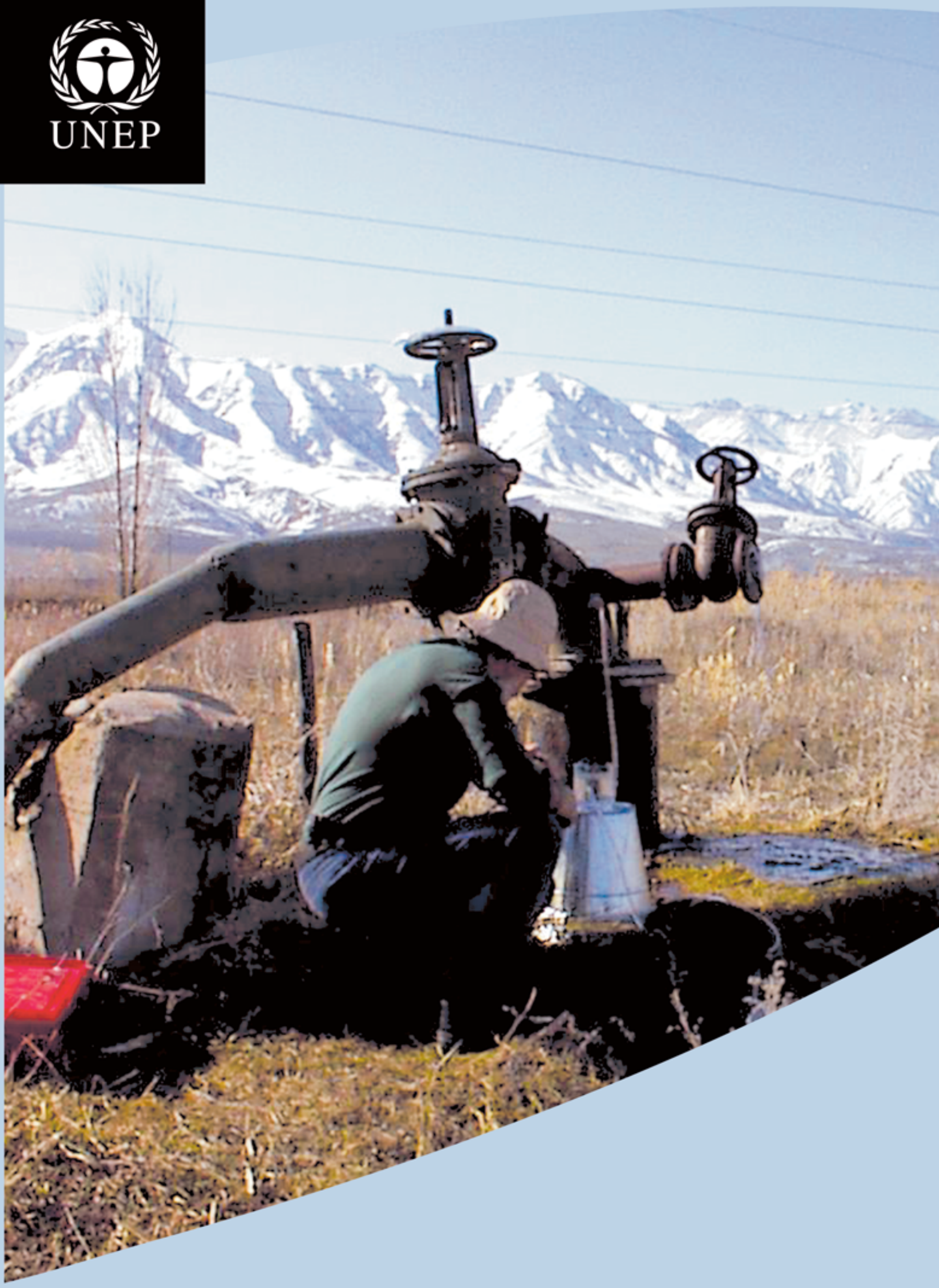
UNEP/DEWA/RS.03-3



UNEP

UNEP

DGDC
Belgian Development Cooperation

DFID Department for International Development

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

# Groundwater and its Susceptibility to Degradation

## *A global assessment of the problem and options for management*

# Groundwater and its susceptibility to degradation:

## *A global assessment of the problem and options for management*

UNEP

DFID Department for International Development

DGDC Belgian Development Cooperation

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNEP/DEWA
DFID

This publication was prepared on behalf of the United Nations Environment Programme's Division of Early Warning and Assessment (UNEP-DEWA) by the British Geological Survey (BGS), which is a component body of the UK Natural Environment Research Council. The principal BGS authors were Brian Adams (Chapter 3), Roger Calow (Chapter 8), John Chilton (Chapter 7), Ben Klinck (Chapter 6), Adrian Lawrence (Chapters 3, 4, 7 and 8) Brian Morris (Chapters 1, 2, 4, 5 and 6, project manager) and Nick Robins (Chapter 6).

*ISBN: 92-807-2297-2*

For bibliographic and reference purposes, this publication should be cited as Morris, B L, Lawrence, A R L, Chilton, P J C, Adams, B, Calow R C and Klinck, B A. (2003) Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management. Early Warning and Assessment Report Series, RS. 03-3. United Nations Environment Programme, Nairobi, Kenya.

*Cover photographs clockwise from top:*
1. Main, front cover: Groundwater's vital role in city water supply; surveillance of periurban wellfield supplying Bishkek (Kyrghyzstan)
2. Top, front cover: Leaking oil production well; potential pollution source on a vulnerable limestone aquifer (Barbados)
3. Middle, front cover: Solid waste disposal needs careful design and siting to minimize pollution risk (UK)
4. Bottom, front cover: Wellhead water quality monitoring; an important aspect of public water-supply surveillance (Bolivia)
5. Top, back cover: Community maintenance of handpump-equipped rural water supply boreholes (Tamil Nadu India)
6. Upper centre, back cover: Sampling a community borehole in a low-income urban neighbourhood (Bolivia)
7. Lower centre, back cover: Village handpump with well-designed protective plinth, soakaway and washing slab (Malawi)
8. Bottom, back cover: Low-income districts in many developing cities depend on nearby aquifers for low-cost water supply (Kenya)



To obtain copies of this publication, please contact:

Division of Early Warning and Assessment
United Nations Environment Programme
P.O. Box 30552
Nairobi 00100
Kenya
Tel: (254 2) 62 41 05
Fax: (254 2) 62 42 69
E-mail: dewainfo@unep.org

Partner organisations in the production of this publication:

Department for International Development
No.1 Palace Street
London SW1E 5HE
United Kingdom

Belgian Development Cooperation
Rue Marie-Terese 1B
1000 Brussels
Belgium

British Geological Survey
Keyworth
Nottingham NG12 5GG
United Kingdom

# CONTENTS

## Figures



## Tables

## Plates



## Text Boxes

**ACKNOWLEDGEMENTS**

We would like to thank UNEP-DEWA and the UK Department for International Development for supporting this publication, and especially Salif Diop and Patrick Mmayi at UNEP who were key motivators during its production.

In addition to the BGS staff acknowledged in the opening page John Bloomfield, Jeff Davies and David Kinniburgh and Magali Moreau contributed to this report. The authors' efforts were greatly enhanced by the skills of the drafting, editing and design team comprising Gill Tyson, Audrey Jackson, Amanda Hill, Brian Morris and Celia Kirby. Mike Price (Postgraduate Research Institute for Sedimentology of the University of Reading) undertook a perceptive and typically thorough technical review. At UNEP, Halifa Drammeh, David Smith, Beth Ingraham, Audrey Ringler and Matthew Fortnum were all instrumental in realising this project, as was Emmanuel Naah at UNESCO/International Hydrological Programme. Willi Struckmeier at the German Federal Institute for Geosciences and Natural Resources (BGR) kindly facilitated use of the latest version of the Groundwater Resources of the World map. Finally, the many examples used in this review were drawn from the work of groundwater professionals of many nationalities, especially from the developing world, a number of whom it has been the authors' privilege to work with. Their contributions to our understanding of this vital global water resource are gratefully acknowledged.

## GLOSSARY OF ABBREVIATIONS AND ACRONYMS*

| | |
|---|---|
| BTEX | Benzene, toluene, ethylbenzene, xylene; aromatic compounds with health guideline limits |
| CEAQ | Comisión Estatal de Aguas de Querétaro (Mexico) |
| DDT | Dichlorodiphenyltrichloroethane, a pesticide once widely used to control insects in agriculture and insects that carry diseases such as malaria |
| DFID | United Kingdom Department for International Development |
| DNAPL | Dense non-aqueous phase liquid |
| DOC | Dissolved organic carbon, with values usually quoted in mg/l |
| ECE | United Nations Economic Commission for Europe |
| Eh | Oxidation potential, with values usually quoted in mV |
| FAO | Food and Agricultural Organisation of the United Nations |
| IPCC | Intergovernmental Panel on Climate Change |
| K | Hydraulic conductivity, with values usually quoted in m/d; a measure of the permeability of a rock |
| LNAPL | Light non-aqueous phase liquid |
| OECD | Organisation for Economic Cooperation and Development |
| PDAM Jakarta | Perusahaan Daerah Air Minum, Jakarta (Indonesia) |
| R | Recharge to groundwater, typically measured in mm/year |
| S | Storage coefficient or storativity; a dimensionless value which is the volume of water which an aquifer releases or takes into storage per unit surface area of aquifer per unit change in head |
| SAGUAPAC | Cooperativa de Servicios Públicos “Santa Cruz” Ltda.(Bolivia) |
| T | Transmissivity, the product of hydraulic conductivity and aquifer thickness, with values usually quoted in $m^2/d$ |
| TOC | Total organic carbon, with values usually quoted in mg/l |
| UNEP-DEWA | United Nations Environment Programme, Division of Early Warning and Assessment |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| UNFPA | United Nations Population Fund |
| US-EPA | United States Environmental Protection Agency |
| WHO | World Health Organisation |

**Note: this glossary does not include abbreviations or acronyms in this publication that are described in nearby text*

# FOREWORD

*From Klaus Töpfer, United Nations Under Secretary–General and Executive Director of the United Nations Environment Programme (UNEP)*

Recently UNEP produced its third UNEP Global Environment Outlook, GEO-3. GEO-3's multi-sectoral regional and global assessment of the state of the environment paid a special attention to the conditions of the world's water resources. The GEO-3 report identified a wide spectrum of existing and emerging water issues that need to be addressed if the world is to achieve sustainable development. Many of these issues were the subject of Governing Council decisions in 2001, prominent among them being decisions to promote regional and intergovernmental dialogue on water, strengthening the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA), improving the strategic framework of global international waters assessment programme and facilitating regional co-operation on the transfer of environmentally-sound technology.

GEO3 draws attention to the fact that the availability and quality of fresh water is rapidly becoming one of the most critical environmental and developmental issues of the twenty-first century. By 2025, countries considered water stressed will host two-thirds of the world's population. Across the globe, groundwater is being depleted by the demands of megacities and agriculture, while fertiliser run-off and chemical pollution are threatening water quality and public health. In the developing world over 80 per cent of all diseases are attributable to unsafe water and poor sanitation; often rivers downstream from large cities are little more than open sewers.

The information provided in GEO-3 confirms that the transboundary nature of freshwater resources, lakes and underground aquifers, presents an opportunity for nations to work together to manage those resources for the benefit of all and that watershed boundaries do not reflect socio-political boundaries. Recent water assessments confirm that developing countries are continuing to withdraw groundwater for domestic, industrial and agricultural use at an increasingly alarming rate. The pollution of aquifers is also on the rise due to a variety of reasons.

To adequately cover groundwater degradation issues at a global level, there is a need to strengthen collaboration and co-ordination between institutions, their programmes and projects. The new GEMS Water Programme, for example, needs to build on its links with WHO, WMO and UNESCO, as well as collaborating institutions such as the British Geological Survey, UCC/DHI and IGRAC. More emphasis should be placed on capacity building and the harmonisation of assessment methods – particularly in developing countries.

Water is life and sound management of water resources is an integral component of the new paradigm for sustainable development – one that allows the steady improvement in living standards without destroying the fragile natural capital of river, marine and groundwater systems.

The establishment of a surveillance network for monitoring the extent and level of aquifer pollution remains one of the key components of effective global groundwater protection. Regional observatories of aquifer vulnerability and degradation could gain valuable knowledge through the comparison of water quality conditions, and the results would be a powerful public awareness tool. This would ultimately increase the chances of closing the gap between policy enactment and enforcement – so often a stumbling block to achieving sustainable water use.

*From Martin Walshe, Senior Water Adviser,*
*UK Department for International Development (DFID)*

The Millennium Development Goals (MDGs) were adopted by member countries of the UN in 2000 as a global consensus on objectives for addressing poverty. Water has a key role in strategies for achieving all of the MDGs, which include a target to reduce by half the proportion of people without access to a safe water supply and a commitment to ensure environmental sustainability.

The 2002 World Summit on Sustainable Development (WSSD) in Johannesburg made an important advance when it placed poverty eradication at the heart of efforts to achieve sustainable development. The Summit brought the development and environment movements together and committed the international community to a systematic effort both to reduce poverty and pursue sustainable development. A new target on sanitation and a commitment to have water resource plans for all countries in place by 2005 were made at WSSD. The importance of water and its fundamental contribution to sustainable development is now recognised, but the contribution of water to poverty reduction will only be realised if it is set in the broader context of social and economic development and environmental improvement.

The last 50 years have seen unprecedented development of groundwater resources. At a regional level groundwater is of huge importance in Africa, Asia and Central and South America. Nationally, countries from Palestine to Denmark are dependant on groundwater and examples of local reliance can be drawn from Mexico City to small villages in Ethiopia. An estimated 2 billion people worldwide rely on aquifers for a drinking water supply. In a rural context, groundwater provides the mainstay for agricultural irrigation and will be the key to providing additional resources for food security. In urban centres groundwater supplies are important as a source of relatively low cost and generally high quality municipal and private domestic water supply. However, concerns are growing over the sustainability of individual water sources and there is a growing need for management strategies that recognise the complex linkages that exist between groundwater supplies, urban land use and effluent disposal.

This production of this book has been partly funded by DFID through the Infrastructure and Urban Development Division water programme. It provides an overview of the susceptibility of groundwater to degradation caused by human activities, including both quantity and quality impacts, and examines the different issues affecting groundwater resources in rural and urban/industrial settings.

# SUMMARY

This publication provides an overview of groundwater occurrence and of the main issues affecting its quantity and quality. We see how the resource is used in our cities, in industry and mining, in agriculture and rural water supply; how it sustains many of our wetlands; how in its own undramatic way groundwater has become an integral part of billions of people's lives. Numerous examples illustrate resource management issues and underline the need for active management rather than *ad hoc* development.

There are some key messages that those involved in planning and managing groundwater development need to note if the resource is to be used in a sustainable way:

*Groundwater is a globally important, valuable and renewable resource*

Its importance stems from its ability to act as a large reservoir of freshwater that provides "buffer storage" during periods of drought. Much groundwater is of good quality water because of natural purification processes, and its typically modest treatment requirements make it a valuable source of potable water which can be developed cheaply and easily, if necessary in a piecemeal fashion

*Groundwater is under threat of degradation both by contamination and by inappropriate use*

Despite its importance, groundwater is often misused, usually poorly understood and rarely well managed. The main threats to groundwater sustainability arise from the steady increase in demand for water (from rising population and per capita use, increasing need for irrigation etc) and from the increasing use and disposal of chemicals to the land surface

*Groundwater needs to be carefully managed if its use is to be sustained for future generations*

Management is required to avoid serious degradation and there needs to be increased awareness of groundwater at the planning stage, to ensure equity ("Fair play") for all stakeholders and most important of all to match water quality to end use (thereby maintaining the best quality for potable use).

Despite the threats from potentially polluting activities, groundwater is often surprisingly resilient, and water quality over large areas of the world remains good. In part this is because many aquifer systems possess a natural capacity to attenuate, and thereby mitigate the effects of pollution, especially of microbial contaminants. As it is impossible to completely avoid aquifer pollution, this capacity should not be underestimated, but instead taken advantage of to minimise the consequences to water supplies and to ecological uses of groundwater.

Although groundwater is not easily contaminated, once this occurs it is difficult to remediate, and in the developing world, such remediation may prove practically impossible. For that reason it is important to identify which aquifer systems and settings are most vulnerable to degradation because the replacement cost of a failing local aquifer will be high and its loss may stress other water resources looked to as substitutes. This can be especially important for urban water supply where, notwithstanding local pollution threats, globally the biggest challenge to groundwater quality is not from high-profile contaminants like arsenic or toxic industrial chemicals but salinisation.

A particular water management difficulty arises from the small scale and incremental nature of groundwater development because highly dispersed ownership/use needs imaginative regulatory and financial measures. In such cases there is often the problem that the generally high quality of much groundwater is not reflected in the value of the uses to which it is put. The longstanding conflict in peri-urban aquifers between groundwater for irrigation versus public water supply is a case in point.

A vital aid to good groundwater management is a well-conceived and properly supported monitoring and surveillance system. 'Out of sight, out of mind' is a poor philosophy for sustainable development. The general neglect of groundwater resources in terms of national planning, monitoring and surveillance will only be overcome once effective monitoring is regarded as an investment rather than merely a drain on resources. For this reason monitoring systems should be periodically reassessed to make sure that they remain capable of informing management decisions so as to afford early warning of degradation and provide valuable time to devise an effective strategy for sustainable management.

# INTRODUCTION

1

## THE WORLD'S HIDDEN WATER RESOURCE

Most of the Earth's liquid freshwater is found, not in lakes and rivers, but is stored underground in aquifers. Indeed, these aquifers provide a valuable *baseflow* supplying water to rivers during periods of no rainfall. They are therefore an essential resource that requires protection so that groundwater can continue to sustain the human race and the various ecosystems that depend on it. The contribution from groundwater is vital; perhaps as many as two billion people depend directly upon aquifers for drinking water, and 40 per cent of the world's food is produced by irrigated agriculture that relies largely on groundwater. In the future, aquifer development will continue to be fundamental to economic development and reliable water supplies will be needed for domestic, industrial and irrigation purposes.

Yet recognition of the pivotal role of groundwater in human development is relatively recent and still patchy. This omission is understandable; water stored in the ground beneath our feet is invisible and so its depletion or degradation due to contamination can proceed unnoticed, unlike our rivers, lakes and reservoirs, where drying-up or pollution rapidly becomes obvious and is reported in the news media.

Part of this book is devoted to describing the ways in which groundwater is vulnerable, and numerous examples are cited of how aquifers are affected in ways that threaten both the quantity and the quality of the water we draw from underground. However, it is not helpful on its own just to catalogue the threats to the resource and cite examples of its degradation by pollution or misuse; some prescriptions for a better approach are needed too if we are to manage groundwater for the future and not just for the present.

The growing recognition worldwide that we need to manage the Earth's fragile natural resources in a more sustainable way is demonstrated by the widespread adoption of the *Agenda 21* manifesto presented at the 1992 Earth Summit in Rio de Janeiro (Box 1). We also need to understand the pressures on our resources, and adopt policies that will help make sustainability a reality. Thus, for groundwater we must determine which environmental processes within the aquifer systems can help to mitigate contamination, which environmental settings are more vulnerable, and how the resources can be managed to conserve them for future use. One of the characteristics of groundwater is that pollution usually takes a very long time to appear in a water source, often decades or longer. In consequence, it is technically difficult and expensive to clean up an aquifer once it is polluted.

**BOX 1 EXTRACT FROM AGENDA 21**

Sustainable development of freshwater: an extract from Chapter 18 of Agenda 21, the Rio Declaration on Environment and Development.

'Water is needed in all aspects of life. The general objective is to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water-related diseases…. The multisectoral nature of water resources development in the context of socio-economic development must be recognized, as well as the multi-interest utilization of water resources for water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation, recreation, low and flat lands management and other activities'.

*(Adopted by more than 178 governments after the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil, 1992).*

## SETTING THE SCENE

### WHY IS GROUNDWATER SO USEFUL?

Groundwater constitutes about 95 per cent of the freshwater on our planet (discounting that locked in the polar ice caps), making it fundamental to human life and economic development. There are many reasons why society has found it so useful to develop groundwater, but among the most important are:

- aquifers are very convenient sources of water because they are natural underground reservoirs and can have an enormous storage capacity, much greater than even the largest man-made reservoirs. For example, in the four decades up to the early 1980s an estimated 500 km$^3$ of groundwater, equivalent to more than three times the total volume of either Lake Kariba or Lake Nasser, was withdrawn from the Ogalalla aquifer that underlies portions of eight states in central USA. Such storage enables timely use of water, which can be pumped out during dry periods when corresponding surface resources such as rivers or reservoirs may be unable to provide enough water;

- many aquifers are also able to offer natural protection from contamination (see later chapters), so untreated groundwater is usually cleaner and safer than its untreated surface water equivalent;
- groundwater is relatively easy and cheap to use. It can be brought on-stream progressively with little capital outlay and boreholes can often be drilled close to where the water supply is needed;
- it is a resource that is organisationally easy to develop; individuals can construct, operate and control their own supply, often on their own land.

## IS GROUNDWATER WIDELY USED?

Globally, groundwater use is enormous, but it is generally recognised that the extent of its use tends to be underestimated, not least because the very ease and ubiquity of groundwater development means that much vital small-scale use is excluded from official statistics. Groundwater is often taken for granted by

**Table 1**
**Population of megacities dependent* on groundwater**

| City | Pop. | City | Pop. | City | Pop. |
|---|---|---|---|---|---|
| Mexico City | 25.8 | Buenos Aires | 13.2 | Cairo | 11.1 |
| Calcutta | 16.5 | Jakarta | 13.2 | Bangkok | 10.7 |
| Teheran | 13.6 | Dhaka | 11.2 | London | 10.5 |
| Shanghai | 13.3 | Manila | 11.1 | Beijing | 10.4 |

*Estimated population in 2000 (UNEP, 1991; UNFPA, 1991)*

** Groundwater dependency definition The city's water supply (public and private domestic, industrial and commercial) could not function without the water provided by a local urban or peri-urban aquifer system. Typically groundwater would provide at least 25 per cent of the water supply to such a city.*


*Figure 2. Groundwater-dependent cities in Africa.*

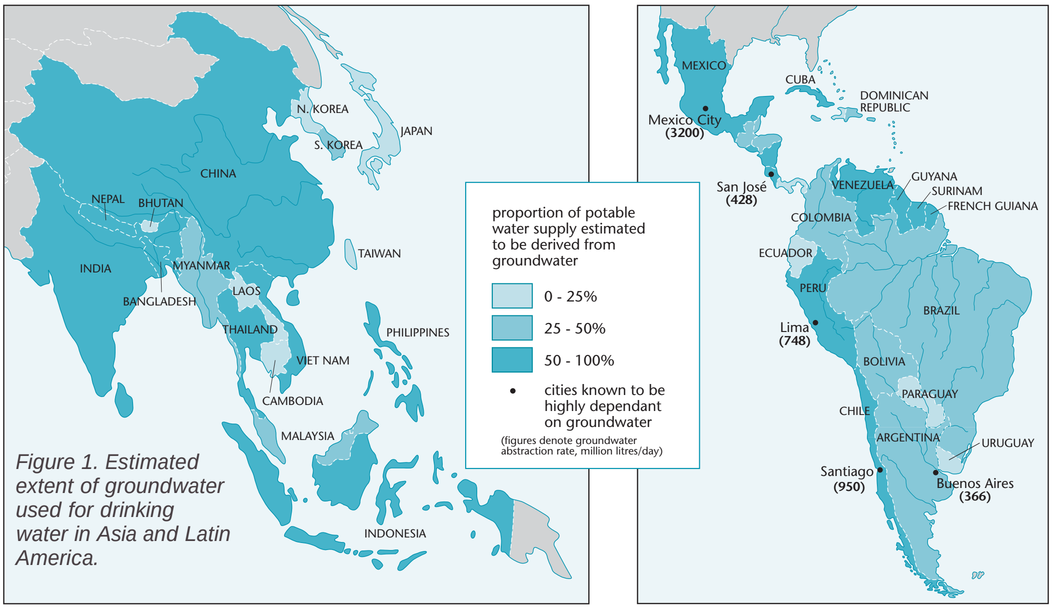



*Figure 1. Estimated extent of groundwater used for drinking water in Asia and Latin America.*

governments and society. The following sections merely give a flavour of its pivotal role in human development.

## Groundwater in cities

In the year 2000, twenty-three cities of the world had a population of more than 10 million, and are thus classed as *megacities*. Over half of these rely upon, or make significant use of, local groundwater (Table 1).

China alone has more than 500 cities, and two-thirds of the water supply for these is drawn from aquifers (Chéné, 1996). This high urban dependency is mirrored elsewhere in Asia and in Central and South America (Figure 1).

Urban reliance on groundwater is independent of climate and latitude. Thus, almost a third of the largest cities of Russia meet their water demands mainly from groundwater, as do many of the capitals of central and west African countries (Abidjan, Bamako, Bangui, Cotonou, Dakar, Lomé, N'Djamena, Niamey, Nouakchott, Ouagadougou) (Figure 2). It is estimated that many hundreds of cities worldwide are groundwater dependent.

## Groundwater in rural areas and small towns

The use of groundwater for domestic supply is even more widespread in smaller towns and rural communities. This is well illustrated in eastern China, where the Huang-Huai-Hai aquifer system supplies nearly 160 million people, and it is estimated that almost one-third of Asia's drinking water supply comes from groundwater. In the USA, more than 95 per cent of the rural population depend on aquifers to provide their drinking water. Reliable and unequivocal global figures are difficult to obtain either because the role of private domestic supply is unquantified or because many towns and cities derive their supplies from a mixture of surface water and groundwater, with proportions changing either with the time of year or with demand patterns. An estimate of the use of groundwater for potable supply worldwide is given in Table 2.

**Table 2**
**Estimated percentage of drinking water supply obtained from groundwater**

| Region | per cent | Population served (millions) |
|---|---|---|
| Asia–Pacific | 32 | 1000 – 2000 |
| Europe | 75 | 200 – 500 |
| Central and South America | 29 | 150 |
| USA | 51 | 135 |
| Australia | 15 | 3 |
| Africa | NA | NA |
| World | - | 1500 –2750 |

*Source Sampat (2000) after UNEP, OECD, FAO, US-EPA, Australian EPA*

**Table 3**
**Selected national statistics on agricultural irrigation and groundwater use (from Foster et al., 2000, based on UN-FAO data)**

| Country | Year | Irrigated area (kha) | Water use ($Mm^3/a$) | Origin of water (per cent)* | |
|---|---|---|---|---|---|
| | | | | Surface | Ground |
| Bangladesh | 1993-95 | 3750 | 12 600 | 31 | 69 |
| China | 1990-93 | 48 000 | 407 800 | 78 | 18 |
| India | 1990-93 | 50 100 | 460 000 | 41 | 53 |
| Pakistan | 1990-91 | 14 330 | 150 600 | 66 | 34 |
| Mexico | 1995-97 | 5370 | 61 200 | 63 | 27 |
| Peru | 1992-95 | 1200 | 16 300 | 89 | 11 |
| Argentina | 1994-95 | 1550 | 18 600 | 75 | 25 |
| South Africa | 1991-94 | 1270 | 9580 | 82 | 18 |
| Tunisia | 1990-91 | 310 | 2730 | 39 | 61 |
| Morocco | 1989-91 | 1090 | 10 180 | 69 | 31 |
| Iran | 1992-93 | 7260 | 64 160 | 50 | 50 |
| Saudi Arabia | 1992-93 | 1610 | 15 310 | 3 | 96 |
| Syria | 1992-93 | 640 | 13 600 | 40 | 60 |

** These statistics do not distinguish supplementary from near-continuous irrigation, or conjunctive use where practised; definition of irrigated land varies between countries*

**Table 4**
**Industrial water use in the world's most industrialised and least industrialised countries**

| Country | Grouping | Industrial Water Use* % | m3/p/year |
|---|---|---|---|
| Canada | ● ▲ | 80 | 1144 |
| France | ● ▲ | 69 | 407 |
| Germany | ● ▲ | 68 | 484 |
| Italy | ● ▲ | 27 | 265 |
| Japan | ● ▲ | 33 | 237 |
| Russia | ● ▲ | 62 | 327 |
| United Kingdom | ● ▲ | 77 | 155 |
| United States | ● ▲ | 46 | 777 |
| Argentina | ▲ | 18 | 134 |
| Australia | ▲ | 20 | 53 |
| Brazil | ▲ | 17 | 37 |
| China | ▲ | 7 | 25 |
| India | ▲ | 4 | 15 |
| Indonesia | ▲ | 4 | 9 |
| Mexico | ▲ | 8 | 63 |
| Saudi Arabia | ▲ | 3 | 14 |
| South Africa | ▲ | 11 | 31 |
| South .Korea | ▲ | 14 | 82 |
| Turkey | ▲ | 11 | 53 |
| Mali | ▼ | 1 | 1 |
| Central African Republic | ▼ | 5 | 1 |
| Chad | ▼ | 2 | 0 |
| Guinea-Bissau | ▼ | 4 | 1 |
| Mozambique | ▼ | 2 | 1 |
| Ethiopia | ▼ | 3 | 1 |
| Burkina Faso | ▼ | 0 | 0 |
| Burundi | ▼ | 0 | 0 |
| Niger | ▼ | 2 | 1 |
| Sierra Leone | ▼ | 4 | 3 |

● *Member of G8 group of leading industrial nations*
▲ *Member of G20 group of industrial and emerging economies*
▼ *World's poorest nations according to human development index HDI, 1999†*

* †*data based on http://www.worldwater.org and http://www.undp.org; includes power plant cooling water*

**Groundwater in agriculture**
During the last 30 to 40 years there has been an enormous rise in food production in many countries through the increased use of irrigation. Much of this irrigation water has been drawn from groundwater as people realise the advantages to increased productivity of timely irrigation and security of application. Table 3 provides a snapshot of recent use, and shows the importance of groundwater in the irrigation schemes of India, China and Pakistan and other agricultural economies. The rapid rate of growth in irrigation is perhaps best illustrated in India, where the amount of land irrigated by surface water has doubled between 1950 and 1985, but the area irrigated from aquifers has increased by 113 times so that by the 1990s aquifers supplied more than half of the irrigated land. Perhaps the best example in the developed world is that of the USA which, with the third highest irrigated area in the world, uses groundwater for 43 per cent of its irrigated farmland.

Irrigation can bring many advantages, but poor management can have disastrous effects both on land productivity (for example land salinisation in the Indus Basin in Pakistan) and on major ecosystems (for example in the Aral Sea in Central Asia).

**Groundwater in industry**
Much of the world's industry is concentrated in developed and rapidly emergent economies. Third World economies account for only about 14 per cent of the world's industry and of this 60 per cent is concentrated into nine countries, mainly in south-east Asia and Central and South America. This pattern is reflected both in the percentage of water withdrawn for industrial use and in the per capita volume of water used in industrial production, as the sample figures in Table 4 demonstrate.

Only a small proportion of the income generated from the use of Third World commodities is returned to their economies, so it not surprising to find that only a very small amount of this total revenue goes towards ensuring adequate environmental controls on polluting activities by industry in developing countries. Indeed some would have us believe that some companies involved in industry and mining in the Third World take advantage of inadequate, or poorly policed, environmental legislation to exact the maximum financial benefit from their operations, disregarding the environment in the process. However, change is beginning to occur, especially as a consequence of global framework instruments such as the 1992 Rio Declaration on the Environment and Development and Agenda 21, now subscribed to by most governments (Box 1).

Although environmental legislation is relatively recent in many newly industrialised countries the process of Environmental Impact Assessment and subsequent implementation of Environmental Management Systems for large-scale mining and industrial projects is more common and is becoming a requirement of much national environmental legislation.

## TYPES OF GROUNDWATER DEGRADATION PROBLEMS

Groundwater degradation occurs where there is:

- excessive exploitation, for example where groundwater levels fall too fast or to unacceptable levels. This not only reduces available water resources and borehole yields but can result in other serious and potentially costly side effects including saline intrusion and subsidence;

- inappropriate or uncontrolled activities at the land surface, including disposal of waste and spillage of chemicals, which contaminate the underlying aquifer. This can arise from diffuse sources, which results in widespread but generally less intense contamination, or from a point source, which causes more intense but localised problems;

- major change of land use, for example in southern Australia, the removal of natural vegetation led to waterlogging and salinisation problems.

The nature of the aquifer will also influence the scale of the contamination problem. Thus, in a highly fractured aquifer where groundwater flow is easy and relatively rapid, contamination may become more widely dispersed in a given time than where flow is intergranular, especially if the strata have only a modest permeability.

Important issues when considering degradation are the use of water, the availability of alternative sources and the scale of impact on different users. Degradation of groundwater often affects the poor most, as they are least able to afford alternative water supplies or to cope with changes in livelihood that deterioration may force upon them.

## GLOBAL WATER ISSUES THAT AFFECT GROUNDWATER

Some global trends affect all of Earth's freshwater reserves. Perhaps the three most far-reaching in terms of resource sustainability are those of salinisation, trends in withdrawals and climate change.

- *Salinisation* Salinity is **the** major threat to aquifer sustainability because it does not reduce naturally, and salinised groundwater can only be made fit for purpose by energy-intensive desalination or by dilution. Salinisation can occur as a result of poor irrigation practice in agricultural areas, and as a result of over-abstraction inducing saline intrusion. The latter occurs usually, but not exclusively, in coastal aquifers. Mixing with just 3 to 4 per cent sea water (or groundwater of equivalent salinity) will render fresh groundwater unfit for many uses, and once this rises to 6 per cent the water is unfit for any purpose other than cooling and flushing. Once salinised, aquifers are slow to recover. In intergranular-flow aquifers, the enormous volumes of water in storage have to be displaced, and in some fracture-flow systems where the matrix is also porous, it is difficult to drain relatively immobile water that has entered by diffusion from the fracture network.

- *Global trends in withdrawals* Freshwater use continues to rise, often at the expense of environmental requirements for the maintenance of

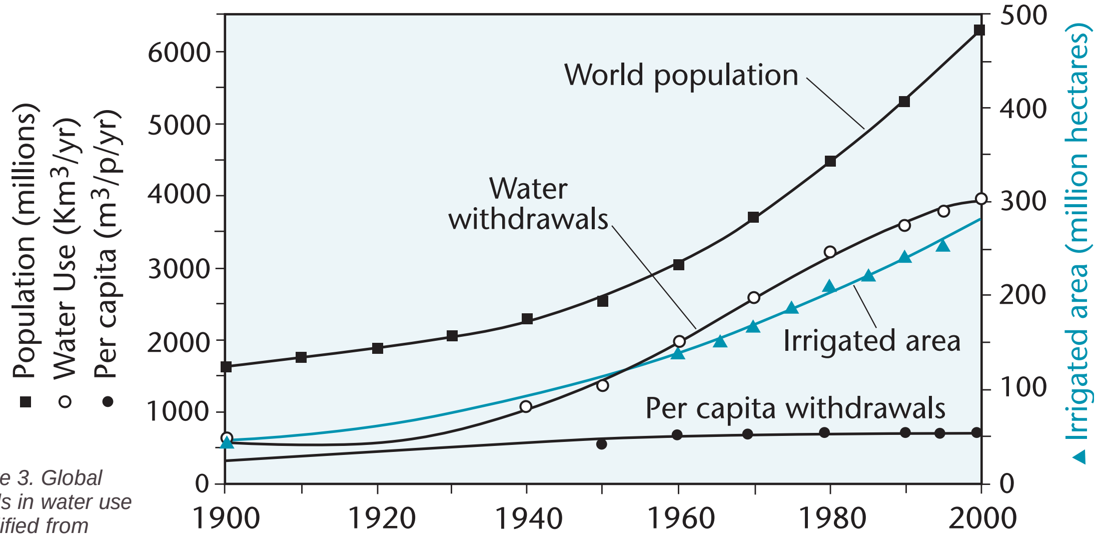



*Figure 3. Global trends in water use (modified from Gleick, 1998).*

ecological diversity. Although separate global figures are not available for groundwater trends, Figure 3 shows a six-fold rise in the total freshwater use between 1900 and 2000, which is not simply related to the increase in global population, as per capita withdrawals during this period only increased by about 50 per cent. Rather, it is the increase in irrigated area and to a lesser extent the growing need for water for industrial uses and power plant cooling that has increased demand.

- *Climate change* Climate change in the 21st century will influence the sustainable management of all Earth's water resources including

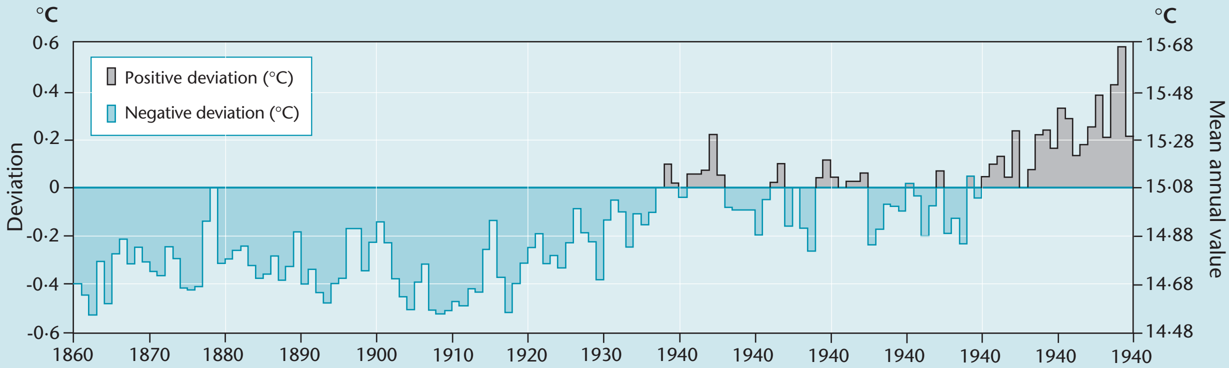
### BOX 2 WHAT IS 'CLIMATE CHANGE'?

Observations of the Earth's climate gives a picture of a warming world and other changes in the climatic system. In addition to the intrinsic variability of climate, changes occur as a result of both natural and human factors. Although natural factors, such as changes in solar radiation or explosive volcanic activity, may affect the global climatic system, the term 'climate change' has popularly come to mean additional changes in the global climate that have been induced by human activities, particularly the emissions of greenhouse gases and aerosols (IPCC, 2001a).

The major greenhouse gases include carbon dioxide (produced when fossil fuels are used to generate energy and when forests are cut down and burned), methane and nitrous oxide (emitted from agricultural activities, changes in land use, and other sources) and various emissions of industrial origin released by industrial processes or disposal, including chemicals called halocarbons and other long-lived gases such as sulphur hexafluoride.

Rising concentrations of greenhouse gases in the Earth's atmosphere cause climate change by enhancing the effects already occurring as a result of water vapour (the main greenhouse gas). By absorbing infrared radiation, these gases trap heat in the lower part of the atmosphere, leading to a warming effect that in turn also influences rainfall patterns, global sea level and the size and extent of the ice caps. Although there are many uncertainties about the scale and impacts of climate change, the balance of the evidence suggests that the climate may have already started responding to recent past emissions and that most of the warming observed over the last 50 years is attributable to human activities.

For example, the global average surface temperature has increased over the 20th century by about 0.6°C (Jones et al., 1999), while average sea level has risen by about 0.1 to 0.2 m during the same period. Changes in rainfall distribution are more complex. Rainfall has increased over land at high latitudes in the Northern Hemisphere, but decreased since the 1960s over the subtropics and the tropics from Africa to Indonesia.




*Trend in global average surface temperature (Source: School of Environmental Science, Climatic Research Unit, University of East Anglia, UK, 1999)*

Climate models predict that the global temperature will continue to increase by about 1 to 3.5°C by the year 2100. Mean sea levels are also expected to continue rising by 0.15 to 0.95 m over the same period. These predicted changes, larger than any climate change experienced over the last 10 000 years, are based on current greenhouse gas emissions trends. Current indications are that if climate change occurs gradually, the impact by 2025 may be minor, with some countries experiencing a beneficial impact while most experience detrimental ones. Climate change impacts are projected to become increasingly strong during the decades following 2025.

## BOX 3 IMPACT OF GLOBAL WARMING

Past and current greenhouse gas emissions have already committed the Earth to some degree of climate change in the 21st century. Likely consequences of global change as people and ecosystems adapt to future climatic regimes can be summarised as follows (IPCC, 2001b).

*Water resources* ~ affected by changes in availability (new precipitation and evaporation patterns), demand (new water supply requirements and possible increased competition for water), and supply (water quality effects).

*Health* ~ weather-related mortality (for example from flooding or drought) and changes in the distribution of infectious diseases.

*Agriculture* ~ changes in crop yields and irrigation demand, increased threats to food security at the global level.

*Coastal areas* ~ damage to physical infrastructure, particularly by sea-level rise and by extreme weather events, coastal erosion and inundation.

*Species diversity and natural habitats* ~ changes in the climatic zones will reduce biodiversity forcing ecosystems to adapt; some systems will decline or fragment with the possibility of some species becoming extinct.

*Costs to society* ~ direct and indirect effects on economic activities, land use and human settlements from changed weather and increased frequency of extreme events.

groundwater. The effects of climate change are likely to be far reaching and in general more severe the faster the rate of change. Some of the causes of climate change, for example the burning of fossil fuels and the emission of halocarbons during industrial processes, are to be found in industrialised countries; others arise from agricultural activities and changes in land use. The negative consequences will be felt worldwide, and are likely to be particularly acute in the developed world where the poor and disadvantaged are the most vulnerable. Past and current greenhouse gas emissions mean that we have already committed the Earth to some degree of climate change in the 21st century. Box 2 briefly describes climate change and Box 3 summarises possible consequences of global warming.

## GLOBAL WATER CHALLENGES AND THE ROLE OF GROUNDWATER

Some striking challenges face those who are responsible for planning and managing the world's water resources in the 21st century.

- *Population pressure* Global population projections indicate that the world population will increase by 20 per cent from over 6 billion in 2000 to over 7 billion by 2015, and to 7.8 billion by 2025, a total increase of 30 per cent.

- *Urbanisation* Cities are growing at a very rapid rate worldwide. The current urban population of 2.8 billion people will increase to 3.8 billion in 2015 and to 4.5 billion in 2025.

- *Public health* Water pollution is responsible for the death of some 25 million people each year, especially in developing countries. Half of the diseases that affect the world's population are transmitted by or through water. Over 2.4 billion people have no acceptable means of sanitation, and more than 1 billion people draw their water from unsafe sources. In 1999, rural water supply coverage was still less than 70 per cent in Africa, Asia and in Central and South America; rural sanitation coverage extended to less than a third of rural households in these regions.

- *Per capita use* As and when water supply, sanitation and other aspects of the standard of living in the developing world improve, so per capita water use will increase. Although the water will not be consumed, its use will have a major effect on water demand and increase commensurately the quantity of waste water that is available for reuse.

- *Global water resources* The consumption of freshwater world wide rose six-fold between 1900 and 2000, more than twice the rate of population growth, and the rate of increase is still accelerating. The effect, when combined with the increase in population, will be to decrease globally the per capita availability of water resources. In Africa, for instance, the per capita annual renewable water resource is predicted to decline by over 55 per cent between 1995 and 2025, from 5700 $m^3$ to 2500 $m^3$.

- *Agriculture* Irrigated land now produces 40 per cent of the world's food, and two-thirds of the world's freshwater withdrawals are used by agriculture. This requires large supplies of water, for example 1000 tonnes of water are needed to grow one tonne of wheat. Salinisation of soils and groundwater is a major threat to water resource sustainability.

- *Industry* Water use is certain to rise as the developing world expands its industry, which was less than 15 per cent of world output in 1990.

- *Biodiversity* In 1996, less than 7 per cent of the total land area of the globe received any form of protection for its flora and fauna.

## SCOPE OF THIS BOOK

This book describes the role of groundwater in the global water infrastructure and how human activities have started to affect this precious resource, in terms both of quantity and quality. The subject is complex and we have limited the discussion of water quality to those aspects that are affected by human activity, and exclude largely those that occur naturally. This division is somewhat arbitrary and not very satisfactory. There are some naturally occurring groundwater quality problems that are a public health issue because the water is not treated, or an environmental problem may arise because an ecological regime has been disturbed. Both aspects could be important in public health and environmental terms. This book attempts to present an overview on how groundwater is vulnerable to degradation by *human activities*, and to offer some cautious advice on how those benefiting from it can start to use this resource in a sustainable way. Future generations are due no less.

*References*
*Bibliography (pp.120-125) numbers 16, 25, 55, 60, 61, 64, 77, 83, 111, 121 and 122 have been used in the production of this chapter.*

# HYDROGEOLOGICAL ENVIRONMENTS

2

This chapter reviews some key characteristics of aquifers and shows how different geological settings will vary in their response to the pressures of water abstraction and pollution.

Boxes 4 and 5 describe the role of groundwater in the Earth's water cycle, how it occurs and the main types of flow system.

## BOX 4 HOW GROUNDWATER OCCURS

Groundwater is part of the Earth's water or *hydrological cycle*. When rain falls, a part infiltrates the soil and the remainder evaporates or runs off into rivers. The roots of plants will take up a proportion of this moisture and then lose it through transpiration to the atmosphere, but some will infiltrate more deeply, eventually accumulating above an impermeable bed, saturating available pore space and forming an underground reservoir. Underground strata that can both store and transmit accumulated groundwater to outlets in rivers, springs and the sea are termed *aquifers.*

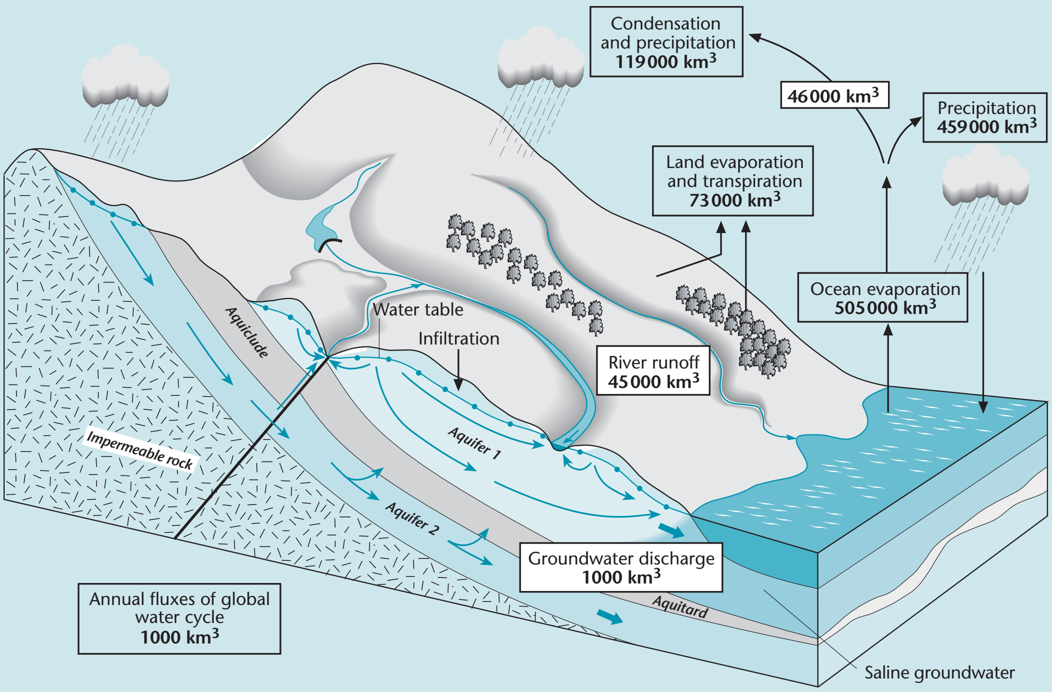



*Figure A. Groundwater in the hydrological cycle.*

The *water table* marks the level to which the ground is fully saturated (*saturated zone*) and reaches the surface at most rivers and all groundwater-fed lakes. Above the water table the ground is known as the *unsaturated zone*.

The productivity of an aquifer depends on its ability to store and transmit water, and these qualities may vary (see Figure A). Unconsolidated granular sediments (Figure Ba below), such as sand or gravel contain pore space between the grains and thus the water content can exceed 30 per cent of the volume. This is reduced progressively as the proportion of finer materials such as silt or clay increases and as consolidation occurs, typically accompanied by cementation of the grains (Bb below). In highly consolidated rocks (Bc below) groundwater is found only in fractures and rarely exceeds 1 per cent of the volume of the rock mass. However, in the case of limestones (Bd below), these fractures may become enlarged, by solution and preferential flow to form fissures and caverns. Even then, the total storage is relatively small compared with unconsolidated aquifers; one result is that there is less water available to dilute contaminated water that finds its way into the system.

**BOX 4 cont.**

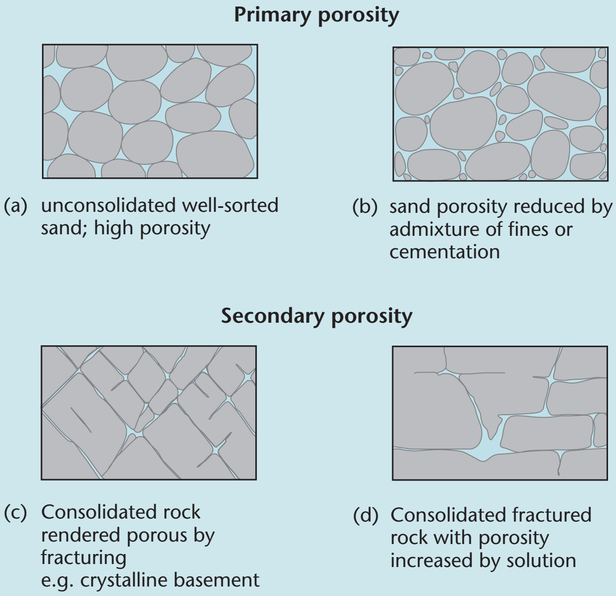



*Figure B. Rock texture and porosity of typical aquifer materials (modified from Meinzer, 1923).*

In the major aquifers, the rock matrix provides a certain proportion of the total storage capacity of the system, while the fractures provide the dominant flow-path.

The most widespread aquifers combine these features and are known as *dual permeability aquifers*, where some regional flow can occur through the matrix and some through structural features such as joints or fault planes. This situation is common in many sandstones. The effect can be enhanced during aquifer development where individual boreholes/well fields may become extra productive after prolonged pumping through preferential near-well development of local fracture systems. This effect has been observed in some Permo-Triassic sandstone aquifers of north-west Europe. Another combination is the *dual porosity aquifer*, such as the important Chalk aquifer of north-west Europe, where the microporous nature of the limestone provides very large but relatively immobile storage, and practically all lateral flow is through fractures. This arrangement greatly modifies pollutant movement, as the water in the matrix is relatively immobile compared with that in the fissures.

## IIMPORTANCE OF DIFFERENT AQUIFER PROPERTIES

### INTERGRANULAR AND FRACTURE FLOW

The productivity of an aquifer depends on the characteristics of the strata of which it is composed. The most important of these properties is whether the porosity is primary (or *intergranular*), so that water is stored in the interstices between the grains, or secondary, where water is stored in and flows through *fractures*. The different ways that water is stored and flows through the rock control both the volume of storage and its relative mobility.

In an intergranular aquifer, the volume of water that can drain under gravity (*specific yield*) may exceed 30 per cent, for example in a medium to coarse-grained sand or gravel that is well sorted (the grains are of a uniform size) and uncemented. This represents a very large volume of storage, and it acts as an important buffer to sudden change, both in water levels and in water quality. For instance, in a 100-hectare (1 $km^2$) area of an aquifer comprised of well-sorted coarse sand, each metre of saturated strata would contain 250 000 to 300 000 $m^3$ of water. Yet quite a heavy rainstorm depositing 50 mm of rain would cause the water table in such an aquifer to rise by no more than 0.2 m, even if all the rain entered the aquifer and none is lost as evaporation or runoff. This large volume of storage means that there is much potential for the dilution of contaminants entering with new recharge.

Much of this water in the interstices is relatively immobile, and flows only very slowly through the matrix. The average linear velocities under natural groundwater gradients are measured typically in metres or tens of metres a year.

## BOX 5 HOW GROUNDWATER MOVES

All freshwater found underground must have had a source of *recharge*. This is normally precipitation (rainfall/snow-melt), but can also sometimes be seepage from rivers, lakes or canals. The recharge typically travels downwards through the unsaturated zone and the aquifer fills up until water reaches the land surface, where it flows from the ground as springs or seepages, providing the dry-weather flow (or *baseflow*) of lowland rivers. Thus the aquifer becomes saturated to a level where the outflow matches recharge.

Shallow aquifers in recharge areas are generally *unconfined*, but elsewhere, and at greater depths, groundwater is often *partially confined* by low permeability strata (an *aquitard*) or fully *confined* by overlying impermeable strata (an *aquiclude*). In confined conditions water may be encountered under pressure, and when wells are drilled, rises above the top of the aquifer, even as far as ground surface, to a level called the *potentiometric surface* (see Figure A).

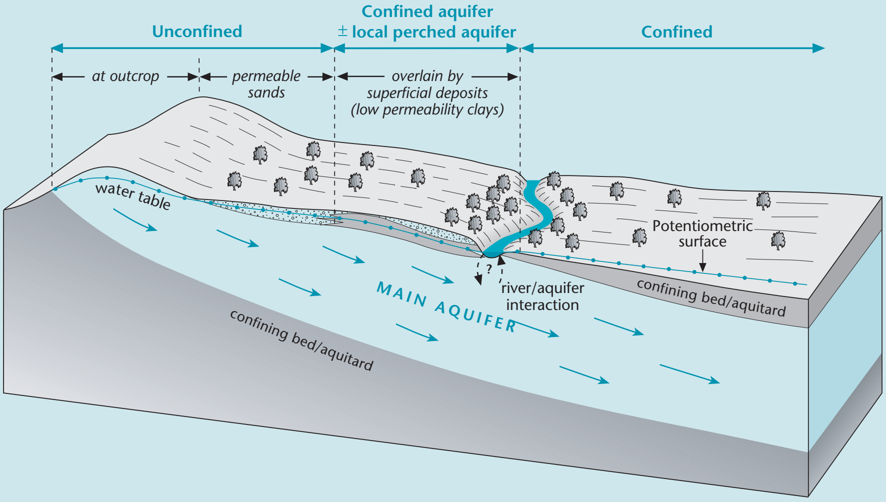



*Figure A. Schematic of a common aquifer situation.*

Groundwater systems are dynamic and water is continuously in slow motion down gradient from areas of recharge to areas of discharge. In large aquifer systems, tens or even hundreds of years may elapse in the passage of water through this subterranean part of the hydrological cycle (Figure B). Such flow rates do not normally exceed a few metres per day and compare with rates of up to 1 metre per second for riverflow. Velocities can be much higher where flow is through fracture systems, dependent on factors like aperture or fracture network density. In limestones with well-developed solution or *karst* or in some volcanic aquifers with extensive lava tubes or cooling cracks, velocities can be measured in km/day. Thus supplies located in different aquifers, or in different parts of the same aquifer, can tap water of widely different residence time. This is an important factor for contaminants that degrade over time and in the control of disease-causing micro-organisms such as some bacteria, viruses and protozoa.

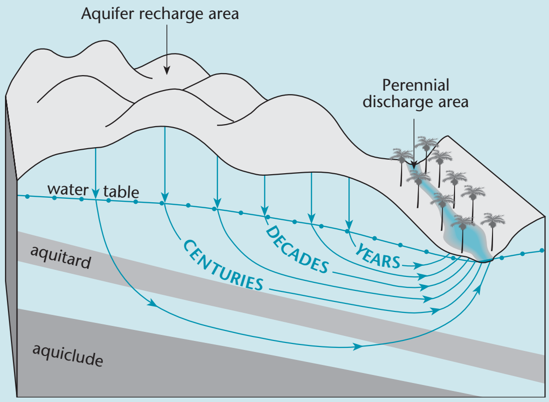



*Figure B. Groundwater flow system in large aquifer.*

As Henri Darcy demonstrated more than 150 years ago, one can predict the rate and volume of flow in an intergranular aquifer with the quite limited information of groundwater gradient, the rock hydraulic properties and some knowledge of the cross-sectional area and aquifer geometry. This makes it easier to predict effects on the productivity of the aquifer, and also how it will respond to different modes of contamination.

In contrast the storage in even highly fractured aquifers is much smaller, and typically does not exceed a few per cent. Thus, the volume of water available for dilution is much smaller. Moreover, the aperture range and degree of interconnection control the availability of the water and the speed with which it flows. Groundwater velocities can be much higher, and may be measured in km/day in some limestone and volcanic lava aquifers, but are also much more variable. It is also technically much more difficult to characterise the fracture density and pattern. This makes for uncertainty in productivity forecasts, in the prediction of the rate and extent of contaminant plume migration, and in the extent to which remediation techniques can be effective.

## LAYERING

Groundwater is found in a wide range of rock types, from ancient crystalline basement rocks that store minor quantities of water in shallow weathered and jointed layers, to alluvial plain sediments that may extend to depths of several hundred metres and contain enormous volumes of groundwater. Sedimentary rocks, in particular, commonly have a strong primary stratification that influences the aquifer system (see Box 5). This layering is hydraulically important because the presence of strata with different permeabilities affects the rate at which contaminants can move into an underlying aquifer. These factors determine the yield, design and depth of the wells that tap such systems.

Layering can also occur in crystalline rocks and metamorphic rocks even though the primary bedding is obscured. It occurs because weathering processes enlarge fractures and introduce interstices near to the ground surface in rocks of otherwise very low permeability. Such rocks may also be overlain by a thin superficial layer of much more recent alluvial or glacial deposits which, if permeable, can provide a temporary storage medium for rainfall recharge, thereby increasing the productivity and apparent storage of the underlying hard rock formation. It results in much more localised flow systems because the aquifer is limited in vertical or lateral extent (Figure 4) as in the case of relatively recent glacial (A) or alluvial (B) sediments, or because the bedrock is highly consolidated and usable water only occurs either in certain fracture systems or in a thin weathered zone near the ground surface (C).

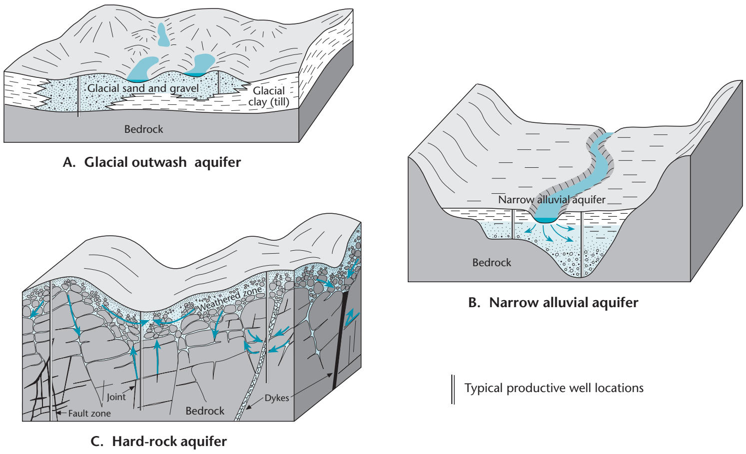



*Figure 4a,b,c. Localised groundwater flow systems in minor aquifers (adapted from Freeze and Cherry 1979, Davis and De Wiest, 1966).*

Residence times in such aquifers are much less predictable either because the degree of interconnection with nearby rivers or lakes is uncertain or there is more scope for rapid by-pass flow along fracture networks. Typically the shortest residence times (hours→days→weeks) occur in karstic limestones or in some lavas and tuffs.

## HYDROGEOLOGICAL SETTINGS

Aquifers can be grouped into broad types that encompass the types of rock, the environments in which they were formed and the effect of subsequent geological processes. All of these factors influence how aquifers respond to the effects of resource degradation. For instance, different settings can:

- permit (or make unlikely) significant stratification of water quality;
- allow the development of major vertical components of flow within the system;
- produce wide variation in the response time or lag between an event, such as pumping or disposal of waste at the ground surface, and the observed response in the aquifer.

The broad classification, based principally on their geological characteristics, genesis and extent is

**Table 5**
**Characteristics of the principal hydrogeological environments**

| Type | Hydrogeological Environment | Lithology | Description/genesis | Extent/dimension |
|---|---|---|---|---|
| Unconsolidated aquifers | Major alluvial and coastal plain sediments | Gravel, sand, silt and clay | Unconsolidated detritus deposited by major rivers, deltas and shallow seas; primary porosity and permeability usually high | Usually extensive in area and of significant thickness |
| Unconsolidated aquifers | Intermontane colluvial and volcanic systems | Pebbles, gravel, sand, clay, and interbedded lavas and tuffs or ash | Rapid infilling of faulted troughs and basins in mountain regions; deposits are unconsolidated, primary porosity and/or permeability is usually high for colluvium and coarse alluvium, modern lavas and ashes, but older volcanic rocks are generally poor aquifers | Much less extensive than alluvial and coastal plain sediments but can be very thick |
| Unconsolidated aquifers | Glacial and minor alluvial formations | Boulders, pebbles, gravel, sand, silt, clay | Ice-transported sediments are commonly unsorted and of low permeability, but water-sorted sediments such as meltwater and outwash deposits have a high porosity and permeability. Alluvial sand and gravel can also be very productive but storage is limited and resource is sensitive to recharge regime | Can comprise relatively narrow channel fills or coalesce to form thick patchy multi-aquifer along piedmont zone |
| Unconsolidated aquifers | Loessic Plateau Deposits | Silt, fine-sand and sandy clay | Usually well-sorted windblown deposits of silt and fine sand, with some sandy clay deposits of secondary fluvial origin; low permeability generally makes subsurface more suitable as receptor than aquifer | Very extensive although deposits may form isolated systems cut by deep gullies |
| Consolidated aquifers | Consolidated sedimentary aquifers | Sandstone | Marine or continental sediments are compacted and cemented to form consolidated rocks; degree of consolidation generally increases with depth and age of deposition. Primary porosity is moderate to poor but secondary porosity from fractures of tectonic origin can be significant | Can form extensive aquifers and be of substantial thickness |
| | | Limestone | Deposited from skeletal material (shell fragments, reefs, reef detritus) in shallow sea. Solution enlargement of fractures can form well-developed cavities/conduit systems (karst features) | |
| Consolidated aquifers | Recent coastal calcareous formations | Limestone and calcareous sand | Composed of coral limestones, shellbanks, chemically precipitated ooids and calcareous oozes; generally loosely cemented; porosity and permeability can be exceptionally high, especially if features are enhanced by solution | Limited area, often forming narrow aquifers that fringe coastline/form oceanic islands |
| Consolidated aquifers | Extensive volcanic terrains | Lava, tuff and ash intercalations | Flows from quiet effusion of mainly basaltic lavas or large explosive eruptions of ash. Primary (interconnected) porosity of thick flows is often neglible but flow junctions and chilled margins can be very permeable if rubbly or degassed. Extremely variable potential; permeability tends to decrease with age | Flood basalts and some ashes are extensive and thick |
| Consolidated aquifers | Weathered basement complex | Crystalline rocks | Decomposition of ancient igneous or metamorphic rocks produces a weathered mantle of variable thickness, with moderate porosity but generally low permeability; underlain by fresher rock, which may be fractured. The combination results in a low-potential, but regionally important, aquifer system | Very extensive, but aquifers are often restricted to upper 30 m or less |

summarised in Table 5 and discussed briefly below, while Plate 1 (page 14) shows the extent of some of the larger aquifer systems.

## UNCONSOLIDATED AQUIFERS

**Thick sediments associated with rivers and coastal regions**

These unconsolidated sediments include many of the world's most important aquifers because very large volumes of groundwater are stored in them and large quantities are pumped from them for water supply and irrigation. They supply water to enormous tracts of irrigated land (for example the Indo-Gangetic Plain of Northern India and Pakistan and the Huang-Hai-Hai Plain of eastern China) and to many urban areas, including the major cities of Bangkok, Jakarta, Calcutta, Dhaka, Hanoi and Shanghai.

These aquifers are almost invariably stratified, with permeable layers of sand or gravel separated by less permeable silty or clayey strata, some in discontinuous layers or lenses. Both the aquifers and intervening aquitards in these systems have high porosities (typically 10 to 30 per cent), providing much potential for dilution. Once pumped, these aquifers can have complex flow patterns because the

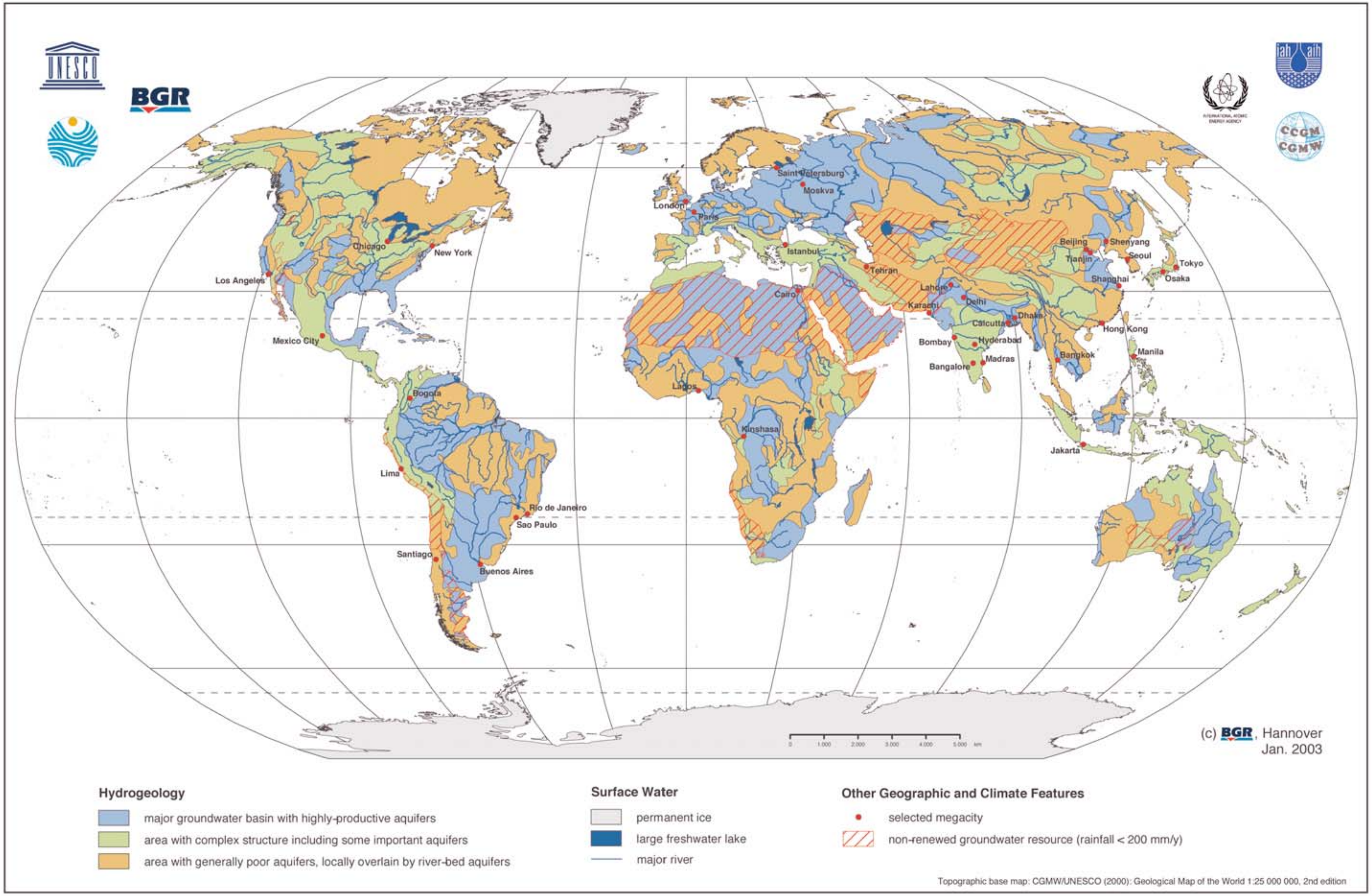



*Plate 1. Groundwater resources of the world.* *(Reproduced with permission of German Federal Institute for Geosciences and Natural Resources BGR, 2003)*

stratification can produce significant vertical head gradients, facilitating movement from one layer to another. Nevertheless, flow velocities both laterally and vertically are typically low so microbiological quality is generally excellent except at very shallow depths and where the contaminant load is very high, as beneath cities. However, the slow travel times also imply a long contact time with the sediment and in some aquifers this can result in significant dissolution of the rock matrix, resulting in mineralisation of the water. The solute content is variable and depends on residence time, the composition of the aquifer matrix and the physicochemical processes. These formations may however be susceptible to subsidence problems caused by pumping.

**Mountain valley, upland and volcanic systems**
Aquifers in this setting result from rapid infilling of troughs and basins within mountain regions. Interlayering of volcanic ash and lava may occur, together with reworked erupted material as volcanosedimentary strata. There are numerous examples of these systems in Central America (such as the aquifers that underlie Mexico City, Chihuahua, León and Guatemala City), and beneath Kathmandu (Nepal) and Sana'a (Yemen). Aquifer permeabilities and porosities are generally high although variable. When combined with above-average rainfall, typical of the climatic regimes where many of these environments are found, valuable aquifers occur and are capable of substantial well yields. Additional recharge to groundwater often occurs where surface water flows from the surrounding mountains and infiltrates the highly permeable valley-fill deposits, especially through alluvial fans and colluvial deposits found on valley margins. The interlayering of volcanic and sedimentary rocks can also generate productive spring systems, as occur widely at sandstone/lava junctions in the Rift Valley basalts of Ethiopia.

**Glacial, Minor alluvial and windblown deposits**
Deposits of glacial and fluvioglacial origin form important aquifers not only in temperate zones of the world but also at altitude in mountain ranges of the Andes and Himalayas. Ice-transported sediments are commonly unsorted mixtures of all grain sizes from clay to boulders; typically, they have low permeabilities, acting as aquitards or aquicludes. Their geographical distribution is usually limited, as they tend to occur in regions of active erosion. In contrast, water-sorted sediments, laid down from glacial melt-water, include sands and gravels that form highly productive aquifer systems. These can be extensive, as in the coalescing gravel outwash plains of North America, the eastern Andes and the Himalayas–Pamir–Tienshan cordilleras, or quite narrow and sinuous, as in the glacial channels of the North German Plain and the Great Lakes.

Deposition from meltwater streams and the upper reaches of braided rivers produces very variable lithologies, forming complex systems in which lenses of highly permeable sands and gravels are partly separated vertically and laterally from each other by less permeable fine sand, silt and clay. Lenticular multi-aquifers are typical of this environment, and the resultant 'patchy' aquifer can be very productive, but hydraulic continuity between different lenses means that mobile persistent contaminants are able to penetrate to significant depths by leakage induced by head differences due to large-scale pumping. On the edge of large mountain ranges they grade into extensive alluvial deposits more characteristic of large river systems, as in the plains east of the Andes and Rocky Mountains and north of the Himalayas.

These aquifers are very widely used for urban supply, either directly by means of boreholes, or as prefilters for high volume riverbank intakes via infiltration galleries or collector wells. A few of the many examples include Cincinnati and Lincoln (USA), Dusseldorf (Germany), Vilnius (Lithuania) and Bishkek (Kyrghyzstan).

Loess, a fine-grained wind-blown deposit, forms an important aquifer in China, and is found elsewhere, for example in Argentina and north of the Black Sea. Thick deposits are almost entirely restricted to north central China where they form vast plateaux covering an area in excess of 600 000 km$^2$; about three-quarters of this area consists of a continuous sheet of loess with a thickness of between 100 and 300 m. The deposits are of low permeability and the presence of ancient soils produces a layered aquifer; the deeper zones are partly confined. The water table is commonly quite deep, 30 to 50 m below surface, but the loess is a key source of domestic water in this semi-arid region of China.

At tropical and equatorial latitudes, minor river systems lay down deposits that, although quite narrow, can provide a water resource of importance out of all proportion to the land area occupied, as in the case of wadi (seasonal river) deposits in desert areas of North Africa and Arabia or ribbons of alluvium on basement rocks in Central Africa.

## CONSOLIDATED AQUIFERS (POTENTIALLY FRACTURED)

**Consolidated sedimentary aquifers**
Important aquifers occur worldwide within consolidated

sedimentary strata, principally sandstone and limestone. Some sandstones retain a primary porosity (porosity between the grains) and are typically of low to moderate permeability. In cemented sandstones (usually found in older formations), the primary porosity is highly variable and, depending on the degree of cementation, the rocks can range from friable to highly indurated. In the latter, it is the secondary (fracture) porosity that provides the aquifer permeability and storage. Sandstone aquifers are important sources of water in Western Europe and North America, in North Africa (Nubian Sandstone), Southern Africa (Karroo Sandstone), in northern India (Tertiary sandstones), in eastern South America (Guarani Complex) and in Australia (Great Artesian Basin).

Even poorly permeable formations can provide a useful groundwater supply in semi-arid zones and regions with a long dry season, where they may be the only source of water. Wells producing only 1 to 2 l/s for instance can be a valuable resource for rural water supply and stock watering. Examples include the Waterberg Sandstone of South Africa and Botswana, the Voltaian sandstones and shales of Ghana, the Continental Terminal sandstones of Gambia, Senegal and tropical West Africa and the Benue shales and limestones of south-east Nigeria. In some cases the productivity of these formations comes from localised weathering rather than more widespread faulting or other structural features.

The vulnerability to pollution of consolidated sedimentary aquifers can be greatly increased where there is a highly developed secondary porosity. Typically this occurs in limestones as a result of solution enhancement of fractures (karst) that permits particularly rapid ingress of water from the surface and movement along enlarged fractures. The resulting aquifers can be prolific, although well yields are highly variable in time and space. Such aquifers are found worldwide, but are important in China, southern and western Europe, in the Middle East and in Zambia. In China alone, karst occupies an area of 2 200 000 $km^2$. The limestones are typically several hundred metres thick, and the groundwater resources are estimated at more than 200 000 MCM /a.

**Recent coastal calcareous formations**
Examples of recent calcareous formations can be found in Jamaica, Cuba, Hispaniola and numerous other islands in the Caribbean, the Yucatán peninsula of Mexico, the Cebu limestone of the Philippines, the Jaffna limestone in Sri Lanka, and some low-lying coral islands of the Indian oceans (such as the Maldives). These formations can form important local aquifers and provide sources of water for cities and for irrigation. Permeability is high to very high and derives both from the initially high primary porosities of the sedimentary rocks and from solution enhancement of fractures. This can produce rapid groundwater movement with velocities frequently in excess of 100 m/d. The high infiltration capacity of these strata means that there are few streams or rivers, and groundwater may be the only available source of water supply in these areas.

These characteristics have important implications for groundwater quality. Soils overlying these formations can be thin, and water movement from the soil to the water table via fractures is often so rapid that even filtration and removal of micro-organisms within the unsaturated zone is not effective. Consequently, these formations are vulnerable to widespread pollution. In addition, as these coastal aquifers are usually in hydraulic continuity with marine water, excessive abstraction with a consequent lowering of the water table may induce sea water up-coning and contamination of the fresh water.

**Extensive volcanic terrains**
Extensive lava flows occur in west-central India, where the Deccan basalts occupy an area of more than 500 000 $km^2$. Other extensive volcanic terrains occur in North and Central America, Central Africa, and many islands are entirely or predominantly of volcanic origin, such as Hawaii, Iceland and the Canaries. Some of the older, more massive lavas can be practically impermeable (such as the Deccan) as are the dykes, sills and plugs which intrude them, and the thick beds of air-fall ashes that may also be extensive in some volcanic areas. However, younger basic lavas provide some of the world's most prolific onshore and offshore springs (Snake River Basalts, Idaho and Hawaii). Individual lava flows can be up to 100 m in thickness. The more massive flows are generally impermeable, although the junctions of many flows can be highly productive, as they may contain shrinkage cracks and rubbly zones caused by the covering over of the rough surfaces of the lava by the chilled bottoms of the next flows. In some terrains, extensive lava tubes may be formed as low viscosity lava drains out beneath a cooled congealed upper surface. The viscosity and gas content of lavas and incandescent ash clouds (welded tuffs or ignimbrites) control not only the compactness, thickness and lateral extent of a flow but also how

rubbly it is likely to be once extruded. These factors in turn dictate the likely storage and water transmitting capacity of a volcanic sequence.

In volcanic terrains where lavas alternate with air-fall ash, productive two-part aquifer systems can be encountered. Highly permeable but relatively thin rubbly or fractured lavas act as excellent conduits but have themselves only limited storage. Leakage from overlying thick, porous but poorly permeable, volcanic ash may compensate for this by acting as aquitards, and are the storage medium for the system. The prolific aquifer systems of the Valle Central of Costa Rica and of Nicaragua and El Salvador are examples of such systems.

**Weathered basement complex**

Over large parts of Africa and in parts of Asia and South America, groundwater occurs in basement aquifers. These are ancient crystalline rocks with little or no primary porosity but groundwater is present in fractures and near-surface weathered layers. In some cases the bedrock has disintegrated into an extensive and relatively thick layer of unconsolidated highly weathered rock with a clayey residue of low permeability. Below this zone, the rock becomes progressively less weathered and more consolidated until fresh fractured bedrock is reached. The zone of weathering is generally only a few tens of metres deep, but in areas of low relief can reach up to 70 m in depth. There are other areas, generally of high relief, where the weathered layer is very variable in thickness and bedrock can occur at the ground surface. As a consequence, groundwater velocities in the weathered and fractured bedrock aquifers can be very variable, as is the pollution vulnerability. Near surface laterite zones for instance can be quite transmissive. Permeabilities even in deeply weathered areas are typically low, but can be sufficient for rural water supplies or small-scale irrigation.

Crystalline basement rocks are commonly used as a source of groundwater because of their wide extent but yields are typically small and the low storage makes boreholes prone to drying up during drought. The disposal of waste water on site to the subsurface in an unsanitary manner can also be a problem for cities. Kampala, Uganda has this problem, where the fractured aquifer occurs at shallow depths, and springs with very localised catchments are easily contaminated. The shallow location of aquifers, the low available storage, localised flow systems and the short residence times for urban recharge all contribute to a setting of high pollution hazard (see Box 26).

*References*
*Bibliography (pp.120-125) numbers 16, 39, 53, 79, 80 and 95 have been used in the production of this chapter.*

# GROUNDWATER EXPLOITATION

3

## USING AQUIFERS IN A SUSTAINABLE WAY

Aquifers serve the important function in the hydrological cycle of storing and subsequently releasing water. The water thus discharged from aquifer storage fulfils two major roles. First, it can benefit the environment by naturally maintaining and sustaining river flow, springs and wetlands. Secondly, it can provide a valuable water supply to meet the growing demand for water for drinking and domestic use, crop irrigation and industry. The reconciliation of these different roles is a major task for those concerned with sustainable use of the Earth's water resources.

In many parts of the world, where rainfall is scarce, groundwater may be the only source of freshwater available and is, as a consequence, often heavily exploited (Box 6).

### BOX 6 AQUIFERS UNDER STRESS

Custodio (2002) has reviewed in depth the various scientific, technical, economic, social and political factors involved in defining over-exploitation, including the contentious issue of whether some of the many instances cited in arid and semi-arid countries are, in fact, over-exploitation. Nevertheless, many countries report serious cases of aquifer stress. Some examples, drawn in part from Custodio's review, are presented in order to give a flavour of the 'quantity' issues as a counterbalance to the 'quality ' issues discussed elsewhere in this book.

**USA**

In 1975, 38 of the 106 water resources subregions of the USA reported overdraft of 30 million $m^3$/y or more.

In Arizona, where groundwater is the only significant water resource, recharge is assumed to be less than half of the 400 million m3/y abstracted, and the average decline in groundwater level has been about 1 m/y since the early 1900s.

By 1980, almost 20per cent of the water in storage in the huge Ogallala/High Plains Aquifer of the mid-West had been removed, with a mean drawdown of 3 m in 40 years and up to 30m locally.

**MEXICO**

The number of aquifers considered to be over-exploited by the federal National Water Commission rose from 32 in 1975 to 36 in 1981 and to 127 by the mid-1990s, principally in the arid and semi-arid states of the north-west, north and centre of the country. Out of 630 aquifers in Mexico, 20 per cent are considered to be over-exploited.

About three-quarters of all groundwater abstracted is used for irrigation. Reported over-exploitation problems include irrigation wells operating with pumping lifts in excess of 100 m, saline intrusion in coastal aquifers in several states, soil salinisation in irrigated areas of Sonora state, land subsidence and damage to property and infrastructure in cities in several upland states including Mexico City, Querétaro, and Celaya.

A water-level depression rate of about 1 m/y in Mexico City is partly responsible for a land-subsidence rate of up to 0.4 m/y and a total subsidence of 7.5 m in 100 years in the city centre.

**SPAIN**

More than half of the 99 hydrogeological units in Spain are officially considered to be over-exploited.

In the important Segura River Basin of eastern Spain, the ratio of groundwater storage depletion to available renewable water resources has increased from less than 20 per cent in the mid-1980s to 130 per cent by 1995.

In the volcanic islands of Gran Canaria and Tenerife, water level depression may be up to 10 m/y in some operating wells and water galleries in the highlands.

The depression of water level can be most striking in some of the smaller aquifers. For example, in Alacant province small aquifers of the Alt Vinalopó valley show a water level decline of 40 to 170 m between 1979 and the late 1990s.

**CYPRUS**

The development of the coastal limestone of south-eastern Cyprus is typical of many similar littoral aquifers in the Mediterranean. Uncontrolled pumping for irrigation in this aquifer, which thins rapidly inland, led to a major reduction in saturated thickness. Between 1960 and 1980, water levels in wells located within a few kilometres of the coast had fallen to more than 25 m below sea level, leading to a major incursion of the sea-water interface and semi-irreversible salinisation of the aquifer to extending several kilometres inland.

**BOX 7 EFFECTS OF PUMPING GROUNDWATER FOR PUBLIC SUPPLY ON NEARBY RIVER FLOWS – A UK EXAMPLE**

A survey commissioned in 1993 by the National Rivers Authority (now the Environment Agency) of England and Wales identified some 40 rivers having severe low flow problems. Of these rivers, 32 reaches were shown to require Low Flow Alleviation (ALF), 27 of which arose from adjacent public water supply abstraction and summer spray irrigation, mostly from groundwater. Management was complicated because most of the abstractions were longstanding, and when licensing was introduced in the early 1960s existing abstractors were given the right to a licence regardless of any environmental implications. This 'Top 40' list has now been superseded by a schedule of sites that is regularly reassessed as part of the regulatory scrutiny of the privatised water supply companies' Asset Management Plans.

An example of one of the 'Top 40' ALF rivers is the River Darent in North Kent, which is fed by springs from the Lower Greensand and Chalk aquifers of the North Downs. Groundwater development since the early 1900s had reached some 113 megalitres/day by the early 1990s, of which about 45 per cent was exported from the catchment to supply parts of London. Moreover, much of the balance of public supply water used within the catchment is not returned to the river as treated waste water until close to its mouth. The abstractions, which were equivalent to half the recharge rate to the catchment, reduced spring flows and dried up the river during the early 1970s and from 1989 onwards. In 1992, the water supply utility (Thames Water) joined with the National Rivers Authority to find a solution to the problem.

The objectives of the amelioration plan were to restore the amenity value of the river by returning enough flow to the channel to provide water for fish, especially trout. An environmentally acceptable flow regime of 50 per cent of the natural flow was established, based on an ecological study and groundwater modelling. An options analysis for reaching this target flow considered reduction in pumping for public supply, river flow augmentation from boreholes, effluent discharge needs and desalination to provide alternative supplies. The chosen scheme centred on reduction in abstraction from sensitive boreholes and the extension by Thames Water of the capacity and flexibility of its distribution network. The Environment Agency and Thames Water jointly funded the scheme cost of £12 million, a good example of cooperation between stakeholders from both the regulatory and the user community.

However, even in countries where there is significant rainfall, conflicting demands on groundwater can lead to shortages (see Box 7)

## THE CONUNDRUM OF SAFE YIELD AND SUSTAINABLE USE

Although groundwater development can have many advantages, such as providing access to safe potable water and improved agricultural production, its use can also have undesirable side-effects such as the drying-up of shallow wells, increasing costs of pumping and deterioration of water quality. Recognising these problems, the idea of a safe level of exploitation or *Safe Yield* has long been discussed. The Safe Yield of an aquifer has been defined as the amount of water that can be withdrawn from the aquifer without producing an undesired result.

At first glance this appears to be reasonable, but what is meant by an 'undesired result' and from whose perspective? Any significant abstraction will necessarily result in some environmental impact by reducing spring discharge or stream flow. Clearly it is important to differentiate the benefits of exploitation from the negative side effects.

More recently the concept of *sustainability* has become current, and is defined as the level of development of groundwater that meets the needs of the present generation without compromising the ability of future generations to meet their needs. The general rationale it represents is clear but each situation needs to be considered on its merits because issues of economics, equity, and the rights of different users are involved in any specific assessment.

For example, the development of deeper groundwater for irrigation may make good economic sense (and be sustainable) both for middle and high-income farmers and for the local economy in general. However, a negative side effect may be the lowering of a shallow water table, which causes village drinking water supplies and shallow irrigation wells belonging to poorer farmers to dry up. Whether this is over-exploitation or not will depend on the viewpoint of the different interested parties (or stakeholders). The exploiter, an affected third party, a licensing authority or regulator and an environmentalist may all have different perceptions. Similarly, views on whether such development is equitable may depend on compensation arrangements for those badly affected. However, although aquifer over-exploitation may be an ambiguous, controversial and somewhat emotive term, it is likely to become more important, especially in the semi-arid regions of the world, as competing demands grow on a limited resource.

The issue is further complicated because water is a dynamic resource. The different components of the water balance vary naturally with time, as during a drought or in response to changing patterns of rainfall. These dynamics also apply to human interventions. For example, increasing groundwater abstraction will cause groundwater levels to decline, which in turn generally reduces other outputs or discharges from the groundwater system, such as the throughflow to the coast, discharge to streams, springs and oases. Human intervention may also increase aquifer recharge, for example in a shallow aquifer by creating storage or in a deeper aquifer by inducing downward leakage into the aquifer. Unless abstraction persistently exceeds recharge a new equilibrium will be reached, but the time taken will vary and depends principally on the dimensions of the groundwater system and the aquifer parameters. It could be many years or even decades, and sustainability considerations must take into account this long time-scale when calculating the response of an aquifer system.

Thus declining groundwater levels are not by themselves a signal of over exploitation, but simply an indication that the system is not in equilibrium. Hydrogeologically there is no objective measure or definition of over-exploitation. Although over-exploitation has usefully been defined as a failure to achieve maximum economic returns to the resource, applying economic analyses to the study of aquifer management may not necessarily include a consideration of the social impact. That a particular aquifer system is becoming or has become over exploited is an economic and moral judgement. The economic factors include considerations of the relative value of different water uses, and the moral factors should take into account the issues of social equity and protection of the environment. The commonest adverse impacts and the hydrogeological factors that control the scale of the consequences are summarised in Table 6.

An example of the difficulty in reconciling sustainability with over-exploitation is the use of the ancient groundwater (palaeowater) beneath central and southern Libya, which was recharged thousands of years ago during a more humid climatic period. 7 million litres/minute of groundwater from over 1000 boreholes tapping the aquifer systems beneath Jabal,

**Table 6 Impact of excessive groundwater abstraction (modified from Foster et al., 2000)**

| Consequences of excessive abstraction | | Factors affecting susceptibility |
|---|---|---|
| Reversible interference | Pumping lifts/costs increase | Aquifer diffusivity characteristic* |
| | Borehole yield reduction | Drawdown below productive horizon |
| | Springflow/river baseflow reduction | Aquifer storage characteristic** |
| Reversible/irreversible *** | Phreatophytic vegetation stress (both natural and agricultural) | Depth to groundwater table |
| | Aquifer compaction/transmissivity reduction | Aquifer compressibility |
| Irreversible deterioration | Saline water intrusion | |
| | Ingress of polluted water (from perched aquifer or river) | Proximity of saline/polluted water |
| | Land subsidence and related impacts | Vertical compressibility of overlying/interbedded aquitards |

* *Diffusivity (T/S) An aquifer response characteristic defined as transmissivity (T) divided by storativity (S)*
** *Aquifer storage characteristic (S/R) Defined as storativity (S) divided by average annual recharge (R)*
*** *Reversible/irreversible These two effects depend on local conditions and the period during which excessive abstraction persists; the immediate response to abstraction is controlled by T/S and the longer term trend by S/R*

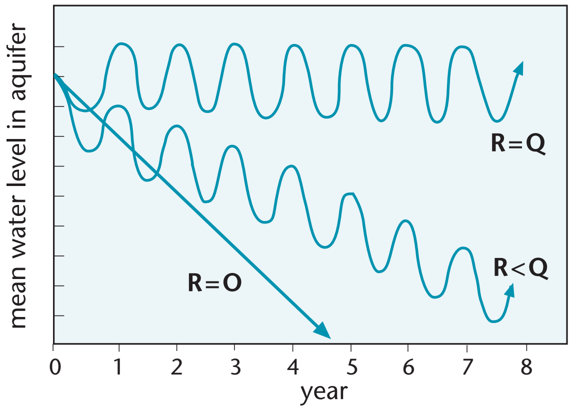
Sarir, Tazerbo and Kufra is transported by large-diameter pipes (the 'Great Man-Made River') to the Mediterranean coast 500 to 900 km away, principally for irrigation purposes. The aquifer system receives effectively no present-day recharge and exploitation of this resource is clearly not sustainable. However, given the very large volumes of groundwater stored (and therefore the long timescales during which exploitation can continue), the significant economic benefit that may accrue, and the limited negative side effects, such groundwater mining may not be, at least by some definitions, over-exploitation.

## NEGATIVE IMPACTS OF OVER-EXPLOITATION

Despite the problem of defining 'over-exploitation' in a given aquifer setting, there are a number of well-known consequences of groundwater development that may not be desirable, which are summarised here.

### GROUNDWATER LEVEL DECLINE AND DECREASE IN SPRING DISCHARGE, RIVER BASEFLOW AND WETLAND AREA

Most aquifers show a water level decline as part of a natural cycle (Figure 5), even when not exploited, at least in some areas for part of the time. (The main exceptions are those aquifers in closed basins where neither recharge nor discharge occurs.) This may be seasonal, during a normal dry season, or it may be longer term in response to a prolonged drought. During these periods river and spring flows and discharge to wetlands are provided by release of water from aquifer storage and, as a consequence, water levels in the aquifer decline. Subsequent periods of recharge permit water levels to rise again as water is brought back into aquifer storage.



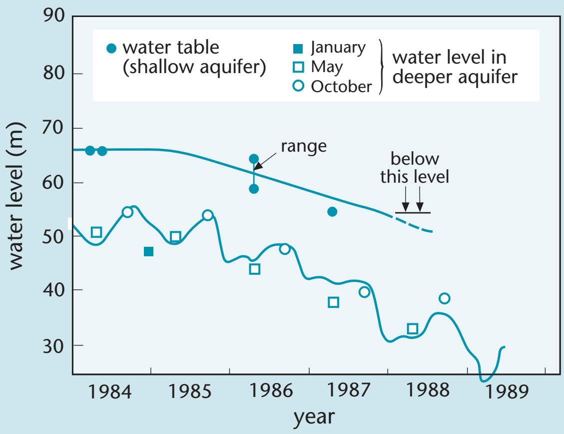

**R=Q** Net recharge = natural discharge and/or abstraction
**R<Q** Natural discharge and abstraction exceed net recharge
**R=O** Abstraction in absence of recharge (arid zone situation)

*Figure 5. Patterns of water level decline in an aquifer under different recharge conditions.*

Likewise, when groundwater is exploited water levels will decline and continue to do so until they either stabilise at a lower level or, if abstraction is persistently greater than recharge, the aquifer is dewatered. Extended declines can result in the drying-up of shallow wells, increased pumping costs, reduced borehole yields and efficiencies, the need to deepen or replace boreholes and, in coastal areas, saline intrusion.

### BOX 8 OVER-EXPLOITATION OF THE MEHSANA ALLUVIAL AQUIFER IN INDIA

For centuries, the Mehsana alluvial aquifer in Gujarat, western India, has been exploited by large diameter, hand-dug wells using animal power. In recent years, deep tube wells that are capable of significant yield have been drilled, and the area of irrigated crops has much increased. The success of these early deep tube wells led to further exploitation of the deeper aquifers and, as a consequence, water levels in both the deeper aquifers and also the shallow water table declined (see graph). In parts of central Mehsana, the fall in the potentiometric level over a 10 year period was almost 60 m. The decline in the water table was not so rapid, but approached 3.0 m/year in the early 1980s and by the 1990s had reached 4.5 m/year.




*Falling water levels in the Mehsana aquifer, Gujarat, India*

The reason for the decline in groundwater levels is that the deeper tube wells do not tap alternative sources of water but instead derive most of their water (about 95 per cent according to modelling studies) as leakage from the overlying shallow aquifer. The modelling studies predicted further large declines in water levels with the result that many of the existing tube wells could become dry.

In extreme cases the aquifer may be effectively dewatered, groundwater levels having become so severely depressed that the aquifer approaches exhaustion. Borehole yields are dramatically reduced and wholesale abandonment results. The resultant forced reduction in abstraction needs to be severe, beyond the long term rate of recharge, for water levels to recover, and this may take many years or even decades to occur.

Such impacts can have severe socio-economic consequences. Declining groundwater levels may also cause drastic reductions in river flow and in wetland areas. The consequences may be slow to develop, not apparent until the problem is well entrenched and may not be reversible (such as the loss of flora and fauna from a natural habitat).

The extent to which water levels fall does not identify whether an aquifer is over-exploited, the important factor is whether the decline is acceptable or not acceptable in terms of the impact on water users and uses. Thus even a water level decline of a very few metres may be enough to threaten an important wetland habitat and be considered unacceptable, yet elsewhere a similar drawdown may be viewed positively as improving drainage and reducing water losses to stream flow and evaporation, and moreover the increase in abstraction for irrigation may permit improved agricultural productivity.

## LAND SUBSIDENCE

Sedimentary formations are initially formed as soft sand, silt or mud. As the sediment builds up and subsequent layers are deposited, the increasing weight of the overburden compresses the lower beds, but the system keeps in equilibrium because the intergranular stress in the skeleton of the formation balances the weight of the overburden. Pressure of the water within the pores between the individual sediment particles also helps to support some of this weight.

Groundwater pumping has the effect of decreasing the *pore water pressure* and thus increasing the effective stress from the overlying strata on the matrix of the aquifer. When the increase in effective stress is greater than a critical value, known as the *preconsolidation stress*, the sediment compaction becomes irrecoverable or *inelastic*. Sedimentary aquifer systems compact in different ways (Box 9).

Subsidence of heavily pumped rural aquifers can affect irrigation and natural land drainage by the reversal of surface topographical gradients but it is in urban areas where the impact can be most serious (Box 10).

### BOX 9 SUBSIDENCE IN DIFFERENT AQUIFER SYSTEMS

In coarse-grained sediments groundwater abstraction results in a rapid readjustment of pore pressure and, if abstraction is excessive, in rapid compaction and subsidence. In fine-grained sediments the response is slower. All sediments are subjected to an increase of effective stress in this situation. However, coarse-grained sandy aquifers form a rigid aquifer matrix which generally resists compaction whereas fine-grained clayey strata are more plastic and hence more prone to compaction. Where relatively coarse-grained aquifers are sandwiched between fine-grained aquitards, groundwater pumping from the coarse layers can induce leakage from the aquitards; the resulting delayed dewatering of the aquitards can result in greater compaction than that of the aquifer. Thus in a multilayered system consisting of coarse-grained aquifers separated by clayey aquitards, cumulative compaction of the aquitard layers can result in significant subsidence at the ground surface. Many observers have noted that there is a ratio of about 0.25 to 0.33 between the total volume of subsidence and the volume of groundwater abstraction in such systems.

During the compaction process a state can be reached where the porosity of the original material is reduced to a point beyond which no significant compaction will occur. The term ‘stable depth’ has been used to define where the weight of the overburden corresponds to the loading required to achieve this state. Thus, stable and unstable fields can be defined as occurring below and above this depth respectively. In areas where erosion processes have removed portions of the uppermost ‘unstable’ strata, the potential for subsidence is reduced. Conversely subsidence is more probable in areas of compaction in which the entire thickness of the more ‘unstable’ section is preserved.

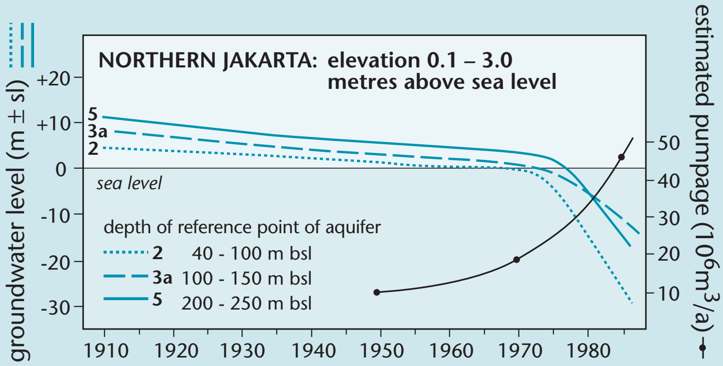
## CHANGES IN FLOW PATTERN LEADING TO DETERIORATION IN WATER QUALITY

Changes in groundwater quality resulting directly, or indirectly, from groundwater abstraction can be classed as over-exploitation if the changes have a negative effect upon the socio-economic value of the resource. Such deterioration in quality can occur for a number of reasons including saline intrusion,

## BOX 10 LACK OF SUBSIDENCE CONTROL IN THE FREE MARKET: JAKARTA, INDONESIA AND BANGKOK, THAILAND

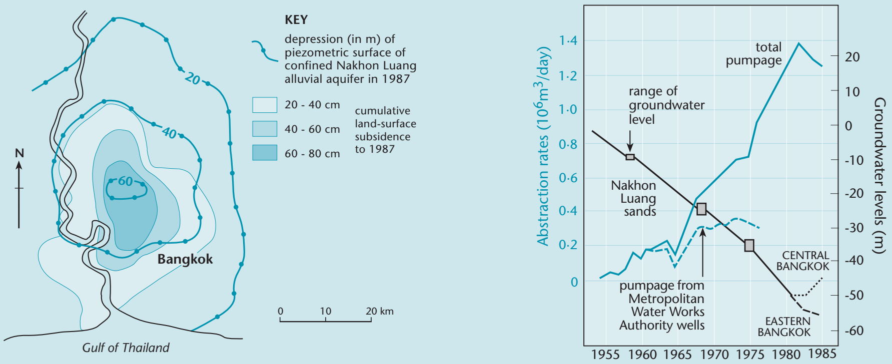
The problems of subsidence control in vulnerable coastal cities is well illustrated by the two south-east Asian cities of Jakarta and Bangkok, which are both located on flat, deltaic land at sea level.

In **Jakarta** (1996 population 8.8 million), the public water supplier PDAM provide water to only 46 per cent of the population (largely from surface water), while the remaining population of 5 million rely exclusively on groundwater. Although there are many unregistered deep wells in operation, it is estimated that up to 90 per cent of the groundwater is derived from the shallow aquifer (less than 15 m deep); this abstraction is entirely uncontrolled and unmanaged. The heavy use of a very shallow (and grossly polluted) aquifer has to some extent mitigated the effect of abstraction on subsidence because water pumped from the shallow aquifer would otherwise be drawn from deeper horizons not so readily recharged by rainfall. Nevertheless, over-pumping from confined aquifers has reduced water levels and critical parts of northern Jakarta, closest to the coast, were suffering by 1990 from saline intrusion as well as subsidence rates of 3-6 cm/year. These effects significantly increase the ever-present risks of flooding from channels during high tides. The lack of control on groundwater abstraction, which is almost entirely by private users as a supplement to inadequate public supplies, is frustrating attempts to instigate flood control measures.




*Falling water levels and rising abstraction in the Jakarta aquifer system. The heavily pumped confined aquifer No. 2 is now subject to leakage from above and below*

In **Bangkok** (1996 population 6.7 million), the shallow subsurface is clay, and so a deep series of alluvial aquifers has been heavily exploited for water supply. This resulted in depression of water levels by up to 60 m by the mid-1980s, producing significant land subsidence and increases in salinity. In contrast to Jakarta, once the severity of the problems created by groundwater overdraft were recognised, successful attempts were made to reduce groundwater abstraction by the Metropolitan Waterworks Authority, and water levels in central Bangkok started to recover. However, no such control was imposed on the private sector and private abstraction, largely by industry, increased such that by the early 1980s it exceeded municipal abstraction by a factor of several times. This has frustrated attempts to manage the aquifer to mitigate the problems. Measures, such as restricting pumping in selected areas and matching pumped water quality to end-use, are made much more difficult when the control of a few large abstractors is exchanged for the much more difficult problem of regulating large numbers of users in a strongly entrepreneurial economy.




*Trends in groundwater pumping and water level in metropolitan Bangkok, with associated cumulative land-surface subsidence* geochemical evolution of groundwater and induced pollution. The induction of flow of low quality water into the aquifer as a result of a new hydraulic head distribution is perhaps the most common of these and is covered in the consideration of aquifer vulnerability to pollution discussed in Chapter 4.

Saline intrusion is an important consideration for aquifers adjacent to the coast or other saline bodies (Box 11). The mobility of such saline waters depends upon the hydraulic gradients (which are of course locally disturbed by groundwater abstraction), the permeability of the aquifer and the presence or absence of hydraulic barriers. A consideration of the time period involved in displacement of a saline front is important to an assessment of over-exploitation. A displacement time of a few years would be a matter of concern, indicating a high probability of 'over-exploitation', but hundreds or thousands of years could well be acceptable in the context of long-term management strategies.

Intrusion of water with dissimilar hydrochemistry can also alter the physical properties of the aquifer. For example, changes in porosity and permeability can result from the processes of consolidating sediments into rock through water–rock interaction. Such processes can irrevocably damage the fabric and hydraulic properties of the aquifer.

Changes induced in the groundwater hydrochemistry due to water–rock interaction may also have detrimental health impacts where the aquifer is used for potable supply. An extreme example is that of arsenic and its deposition from, or solution in, groundwater in certain environments, depending on local physicochemical conditions.

## ASSESSING PROBABILITY OF ADVERSE IMPACTS FROM HIGH ABSTRACTION

### EXCESSIVE ABSTRACTION EFFECTS

The probability of serious adverse side-effects of intense or excessive groundwater abstraction varies quite widely with hydrogeological environment (Table 7). Serious saline intrusion is confined to relatively few hydrogeological settings, but it should be noted that these are not necessarily coastal (see Box 11) as old brackish/saline waters may occur in inland aquifers at depth. Major land subsidence is largely restricted to those coastal alluvial and intermontane valley-fill formations, which contain significant thicknesses of interbedded unconsolidated clay and silt of lagoonal or lacustrine origin. However, a much greater variety of aquifers are susceptible to the induction of polluted recharge if they experience excessive abstraction in urban areas.

### BOX 11 AN EXAMPLE OF GROUNDWATER OVER EXPLOITATION FROM INNER MONGOLIA

The Yao Ba area of Inner Mongolia in the People's Republic of China has been developed since the early 1970s as a desert oasis settlement supporting over 7000 people. By the early 1990s the irrigation scheme consisted of an area of about 35 km2 irrigated with groundwater from 283 boreholes. As the largest groundwater irrigation scheme in north-west China, it was seen as an important model for the region. However, increasing salinity in some of the boreholes was threatening the livelihood of this farming community.

An investigation into the cause of the decline in water quality included the development of a three dimensional groundwater flow and transport model. The inability of the model to reproduce the observed changes in salinity led, against expectation, to the conclusion that advective transport of saline water from an adjacent area was not the predominant mechanism involved. It was concluded that the salinity existed locally throughout the irrigation district in silt and clay strata, and was being released through delayed drainage of these layers following the regional decline in water levels caused by the irrigation abstraction.

Thus, the decline in groundwater levels was apparently having two major impacts on economic returns—an increase in pumping costs and a decline in crop yields as a result of the increasing salinity.

The potential severity of such side-effects can be estimated in a general way if some quantitative information is available on the hydrogeology of the aquifer system concerned (Table 8).

Although these tables can provide a preliminary estimate of susceptibility, detailed hydrogeological investigations are required to make a full diagnosis of the situation and to model probable future scenarios under various management options. For instance, the degree to which well yields decrease due to local or regional over-abstraction of groundwater resources depends on certain detailed hydrogeological features, such as the available drawdown above major

**Table 7 Susceptibility of different hydrogeological settings to adverse side-effects during excessive abstraction**

| Hydrogeological setting | | Type of side-effect | | |
|---|---|---|---|---|
| | | Saline intrusion or up-coning | Land subsidence | Induced pollution |
| Major Alluvial and Coastal Plain Sediments | *coastal* | ✓✓ | ✓✓ | ✓✓ |
| | *inland* | ✓ | ✓ | ✓✓ |
| Intermontane valley-fill: | *with lacustrine deposits* | ✓✓ | ✓✓ | ✓ |
| | *without lacustrine deposits* | ✓ | ✓ | ✓✓ |
| | *with permeable lavas/breccias* | ✓ | - | ✓✓ |
| | *without permeable lavas/breccias* | ✓ | - | ✓ |
| Glacial deposits | | ✓ | ✓ | ✓✓ |
| Loessic plateau deposits | | ✓ | ✓ | - |
| Consolidated sedimentary aquifers | | ✓✓ | ✓* | ✓ |
| Recent coastal calcareous formations | | ✓✓ | - | ✓✓ |
| Extensive volcanic terrains | | ✓✓ | - | ✓ |
| Weathered basement complex | | - | - | ✓✓ |

✓✓ *major effects* ✓ *occurrences known - not applicable or rare*
* *Can occur where associated with overlying compactable aquitards, for example London Basin, UK*

**Table 8 Factors affecting the susceptibility of aquifers to adverse side-effects from excessive abstraction (modified from Foster, 1992)**

| Factor | Symbol | Units | Susceptibility to adverse side-effects: High → Moderate → Low | | | |
|---|---|---|---|---|---|---|
| Aquifer response characteristic | T/S | $m^2$ /day | 100 000 | 1000 | 100 | 10 |
| Aquifer storage characteristic | S/R | - | 0.1 | 0.01 | 0.001 | 0.0001 |
| Available drawdown to productive aquifer horizon | s | m | 10 | 20 | 50 | 100 |
| Depth to water table | h | m | 2 | 10 | 50 | 200 |
| Proximity of saline-water interface to abstraction zone | L | km | 0.1 | 1 | 10 | 100 |
| Vertical compressibility of associated aquitards | $\alpha$ | $m^2$ /N | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ | $10^{-9}$ |

*T transmissivity ($m^2$ /day); S storativity (dimensionless); R average annual recharge rate (mm/year)*

groundwater flow horizons within the aquifer associated with highly permeable geological features (such as exceptionally coarse or highly fractured beds). Where these occur at a shallow depth spectacular yield reductions and unexpected well failures can sometimes occur. In other situations there will be a gradual reduction over periods of decades as the saturated thickness and length of producing screen decline, or individual producing horizons are progressively dewatered (Box 12).

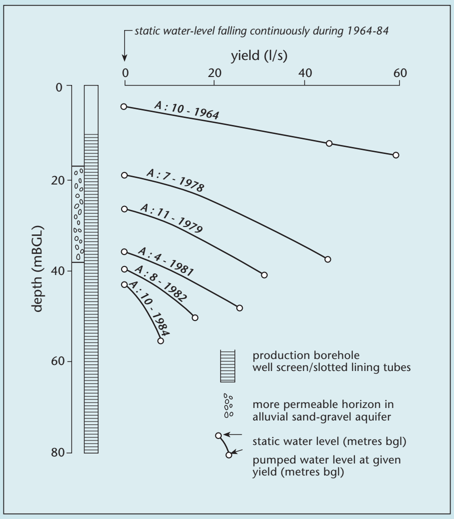
## CONCEPT OF AQUIFER SUSCEPTIBILITY TO OVER-EXPLOITATION

The time scale is an important consideration in the assessment of susceptibility of an aquifer to groundwater level decline. The more susceptible an

## BOX 12 EXAMPLES OF THE IMPACT OF HEAVY ABSTRACTION ON URBAN PUBLIC SUPPLY BOREHOLE PRODUCTIVITY

*Lima (Peru)* The alluvial fan aquifer of Lima and its port Callao was exploited in the late 1980s by more than 320 municipal production boreholes, which provided a supply of up to 650 Ml/d. Many other private industrial abstractors also tap the same resource. This is an extremely arid area, and diffuse recharge from excess rainfall is virtually negligible. Total abstraction since the mid-1970s has considerably exceeded the other forms of aquifer recharge. Over a substantial area the water table was falling by a rate of more than 2 m/a, and in extreme cases by more than 5 m/a. In consequence, there was a dramatic reduction in the yield of production boreholes, especially in areas where the most permeable horizons of the alluvial aquifer occur relatively close to the original groundwater table (see Figure A). In other areas, borehole yields have been less affected.

*Figure A. Decline in operational performance of a production borehole in heavily over-exploited alluvial aquifer, Lima Peru.*




*Dhaka (Bangladesh)* Dhaka is one of the world's largest groundwater-dependent cities, relying on water withdrawn from an underlying semi-confined sand aquifer. A rapid rise in well construction in both the private and public sector in recent years has produced an estimated 1300 boreholes that tap the aquifer in urban and suburban parts of the city. Analysis of construction records for 342 public supply wells drilled between 1970 and 2000 shows that water levels are falling in several areas of the city. Although aquifer water levels have declined by 40 m in the most heavily pumped areas, elsewhere water levels are much less affected (Figure B). The productivity of new boreholes as measured by specific capacity (yield per unit drawdown) has also declined by almost 30 per cent over the same period, from 6.3 l/s/m in the 1970s to 4.5 l/s/m in 1991 to 2000 (Figure C). The aquifer is still too poorly characterised to predict whether this decline will continue at a similar rate.

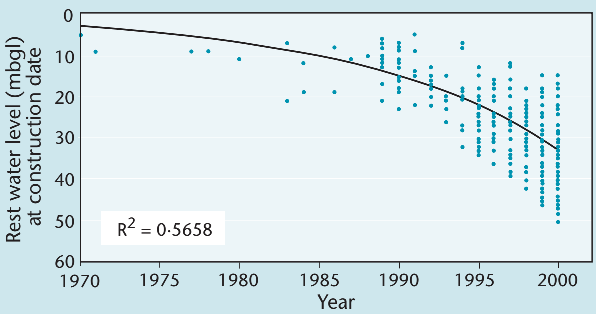



*Figure B. The graph shows the decline in the rest level of water in Dhaka public supply wells, recorded on the date of construction, 1970 to 2000 (from Morris et al., 2003).*

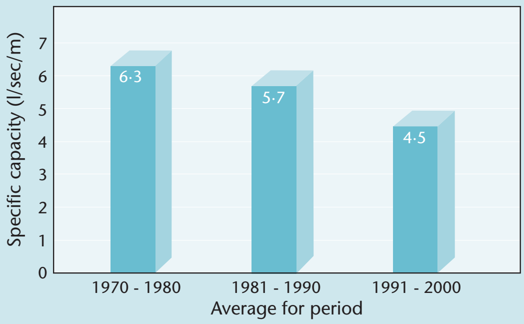



*Figure C. Productivity decline in newly commissioned Dhaka public supply wells, 1970 to 2000 (from Morris et al., 2003).*

In both cities, the overall effect on the municipal water supply has been to raise the number of operational boreholes required to maintain groundwater abstraction volumes and to increase both the unit energy costs of water production (by 25 per cent during 1975 to 1985 in Lima) and the depth and capital cost of new production boreholes in the most affected areas.

aquifer is, the sooner the impact is likely to become apparent. For example, a fractured aquifer of high hydraulic diffusivity (T/S) and limited storage volume is likely to exhibit a more rapid decline in groundwater level than an extensive intergranular aquifer characterised by high aquifer storativity. Where the response of an aquifer to exploitation is rapid, then the opportunity to mitigate negative side effects before they become well established is commensurately limited.

Conversely, in a less responsive aquifer, a slow progressive decline provides opportunities to fully evaluate the problem and identify options to manage or mitigate the worst effects:

- there is time to test and gauge the effectiveness of different economic incentive/disincentive schemes to discourage overuse or to redirect abstraction;
- state agencies may have time to strengthen laws and institutions in order to enforce strict controls on groundwater abstraction;
- perhaps, even more importantly, when enforcement of controls on abstraction are ineffective, there is time for many water abstractors to continue until they have recovered their investment and can redeploy to other areas of economic activity.

## RISK OF GROUNDWATER DEGRADATION DUE TO OVER-ABSTRACTION AND OPTIONS TO MITIGATE ITS IMPACT

The risk of a groundwater resource being severely depleted will depend both on the aquifer susceptibility and the demand imposed upon it in the form of abstraction and natural drainage. Thus an aquifer may have high susceptibility to groundwater level decline but the risk may be low because the abstraction is low. Conversely, an aquifer may have low susceptibility but be at risk because groundwater abstraction is high. Nevertheless any aquifer is at risk if abstraction is high, sustained and well in excess of available recharge. Management responses must therefore recognise that the susceptibility cannot be changed but demand can be controlled.

There are three ways to help control groundwater levels in such a way as to avoid or at least mitigate the negative side effects of aquifer exploitation:

- control the quantity of groundwater abstracted;
- relocate the abstraction boreholes;
- modify the timing of abstraction.

Controlling the quantity of the groundwater pumped is the most important option, and the only option if regional groundwater levels and subsidence are to be stabilised. The options of relocating abstraction boreholes and modifying the timing of abstraction can however help stabilise water levels locally, for example to prevent saline intrusion, protect critical water supply boreholes or limit dewatering of wetlands. However, controlling groundwater abstraction presents many problems.

i It is often unclear who owns groundwater and, by default, the landowner often assumes a right of free access and unlimited use. Given the common pool nature of the resource and lack of appreciation of its volumetric size or limits, it is often subject to unrestrained capture with little or no incentive to conserve or protect. This is in sharp contrast to access and use of river water where there is a long history in numerous societies of established custom or law to recognise upstream stakeholders' rights, protect the interests of downstream users and conserve the resource.

ii Even where laws governing ownership and rights to groundwater exist, the enforcement often lies with agencies that are under-resourced or with poorly defined authority. Difficulty in enforcing controls is common.

iii Economic instruments designed to conserve water or increase pumping costs can result in greater inequalities. For example, richer farmers continue to pump because they can afford to pay while poorer farmers cannot.

iv One of the principal advantages of groundwater is its ability to be developed on a small scale, incrementally and with only modest capital outlay, but in a regulatory sense this is also its greatest disadvantage. The relative ease of development compared with a large river or reservoir scheme can result in many small users of groundwater, and obtaining a consensus of opinion on management objectives for the resource and on enforcing restrictions presents many difficulties. There can be many interested parties (stakeholders) with conflicting opinions—environmentalists versus abstractors, irrigation versus urban supply, public supply versus private abstraction, shallow versus deep groundwater users, urban infrastructure (subsidence) versus abstractors—the views of many such interest groups can be involved in a given over-abstraction scenario.

v Wider policies of the government which are not directly related to water management may unwittingly encourage greater water use. Thus a blanket subsidy on rural electricity can stimulate the rural economy in many ways (enable small rural enterprises such as milling, empower education and relieve pressure on forest resources used for charcoal) but may also stimulate use of electric water pumps and reduce the unit cost of water. Or subsidising the import of basic foodstuffs that require little irrigation can encourage local farmers to cultivate high-priced, water intensive crops.

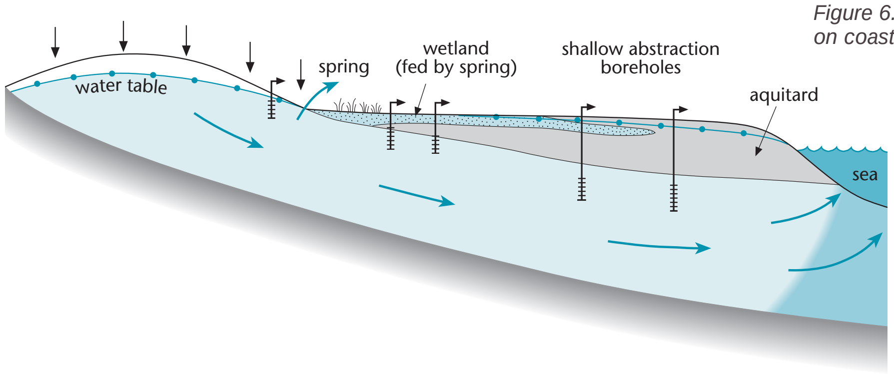
There are a number of ways to effect stabilisation of groundwater levels.

**'Do nothing' approach** This option is more often the unintended outcome of weak or ineffective regulation than an overt policy decision. With no restriction on groundwater development, abstraction increases with time, groundwater levels decline, pumping costs increase and shallow wells are abandoned. The impact can be catastrophic on those who can not afford to deepen their wells or pay for the increasing pumping costs. Typically, rural community water supply wells are hard hit.

Later, other groundwater impacts (such as subsidence or saline intrusion) or economic impacts (such as the decline of irrigated agriculture) may cause serious financial problems to those who have had little role in causing groundwater level depletion. The practical difficulties of reversing the salinisation of an aquifer once extensive intrusion has occurred can seriously prejudice its future usefulness as a water supply source for many years. The potential for conflict between different stakeholders is thus considerable and the political implications are serious.

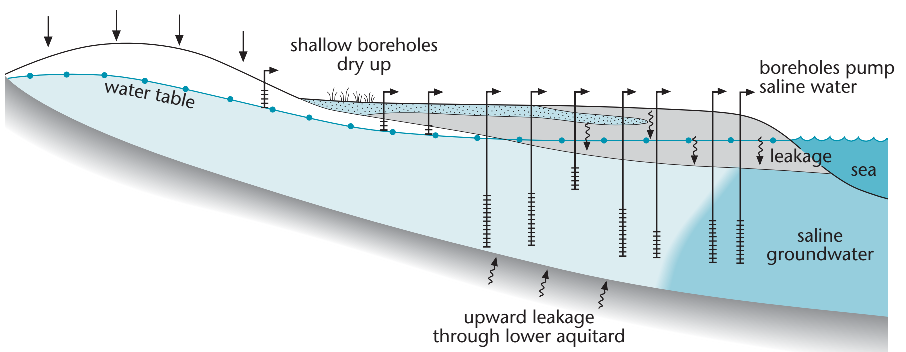
In time, groundwater levels are likely to reach a new equilibrium. Pumping typically stabilises or reduces due to the increased cost of pumping, poor quality of the water, abandonment of abstraction wells or aquifer dewatering. Natural groundwater discharge from the aquifer diminishes as baseflow to surface water or throughflow to the coast decline. In some cases, recharge increases, for instance, by increased leakage from overlying or underlying aquitards. London is a good example of this process.

*Figure 6. Typical impact of excessive abstraction on coastal/lowland aquifer system.*




**Stage A : Initial condition**

- groundwater flows from outcrop to coast
- springs help maintain wetland
- limited abstraction from shallow boreholes occurrs




**Stage B : Groundwater abstraction increases leading to:**

- groundwater level decline in aquifer
- springs feeding wetland cease
- shallow wells dry up
- coastal boreholes become saline
- leakage through upper and lower aquitards (if present) begins

**Control by regulation** Regulation requires some 'Water Authority' or agency with powers to:

- set objectives (abstraction targets);
- monitor;
- enforce compliance.

The authority will need to review and balance the rights and needs of different stakeholders. Efficient management of the resource that avoids being either over-restrictive on abstraction or too lax requires a good understanding of the aquifer system. Information is required on aquifer geometry, working estimates of recharge rates, through-flow and aquifer hydraulic characteristics, and an up-to-date knowledge of water level and abstraction trends. A numerical model would be needed if prediction of water level response to different abstraction regimes were required.

The main advantage of the regulatory approach is that it is possible to look after the interests of less influential and weaker stakeholders, and to protect resources that have a wider national or strategic importance such as wetland sites and critical urban water suppliers. The main disadvantages are the investment required in hydrogeological investigations, the data gathering needed to manage the resource effectively and the difficulties in monitoring and enforcing abstraction controls

**Control by economic instruments** Typically, these rely on steering users by means of financial incentives or disincentives. Thus, for example, industrial water users competing with urban water supply might be offered the incentive of subsidies to invest in more water efficient technologies or to relocate to a less sensitive area, or the disincentive of levies on certain low-value uses (such as once-off use for cooling purposes) to encourage process improvements. Urban public water supply charges (tariff structures, meters, use categories) can be used not just for cost recovery purposes by the water utility but also to control demand, especially where per capita water use is profligate.

Such instruments have the advantage of being rapid to enact, easy to adapt and cost-effective, but need to be seen to be equitable. Thus a municipally run water utility increasing the subscribers' water rates in order to encourage more careful use of water would be tolerated if it is seen to be even-handed. For example, rate-exempted municipal and government offices are common and are notoriously wasteful in water use. Similarly, commercial water utilities engaged on demand management measures need to be seen to be controlling leakage from their own pipe networks if the measures are to retain credibility and public support. The complementary use of regulation and economic incentives or disincentives can be very effective.

Also, the system cannot run itself in that monitoring is still required to gauge the effectiveness of various measures, and these need to be assessed against targets, either in terms of total volume of abstraction or (more practicably) of aquifer water level.

**User-group approach** This approach is likely to develop where an external authority is absent, weak or ineffective, but the groundwater user-community see the need to control abstraction in the best interests of the wider community. Such initiatives are likely to develop where a problem, or potential problem, is perceived, where the user community are stakeholders with broadly similar interests and perspectives, and where there is an organization to provide leadership.

The user group approach is similar to that of the regulatory approach although defining the safe level of development is likely to be more improvised and national or strategic interests are likely to be secondary to the direct interest of the user community.

## IMPACT OF GROUNDWATER LEVEL DEPLETION ON SOCIETY

When evaluating the impact of groundwater depletion on society, two key issues are usually considered. These are the level of reliance upon groundwater and the marginal cost, which is the cost of providing replacement supplies from another source. The argument runs that if groundwater is not widely used then the loss of the resource is unlikely to have a significant impact either on society or the economy, especially where alternative sources of water are available at only a marginal increase in cost. However, there are many areas of the world where groundwater is either the only source of water, because surface water resources are inadequate, or replacement sources of water would be prohibitively costly (for example involving transfer of water between basins). So there is a scarcity value to the groundwater resource. In addition, the argument ignores the intangible but nonetheless real benefits to society of the role of groundwater in maintaining habitat and species diversity.

Also, it must not be ignored that groundwater and surface water are often linked; the perennial flow of many rivers is sustained by groundwater and a decline in groundwater level may reduce this baseflow. The reduction in total flow volume is often secondary to the loss of timely availability of flow, be it for irrigation during the dry season, for dilution of urban or industrial waste-water or for maintenance of riverine habitat.

Groundwater used for irrigation is rarely costed on the basis of its scarcity value or the value of alternative or competing uses. In some cases, it may contribute relatively little added value and, if the farmers paid the full economic value of the water, free of direct and indirect subsidies, then irrigation would not be economically viable. It is generally recognised that domestic water supply, especially to urban areas, has the highest economic and societal value and this makes it a priority use. Yet the assignment of relative value is not straightforward, and each case needs to be judged on its merits. For instance, many cities function perfectly well with per capita water use of 150 to 250 l/p/day, yet others in similar climatic and developmental circumstances are profligate, consuming 500 to 600 l/p/day or even more as a result of poor water management. On the margins of these same cities there may well be horticultural farms producing vegetables and fruit with highly efficient drip irrigation techniques to control nutrient and water application. Who is to say in such circumstances that public supply has the higher value and must be given priority in water resource planning?

Undeniably however, the higher the value of the water use, the more economically feasible it is to provide an expensive alternative supply. Thus interbasin water transfers may be viable where large urban centres are likely to suffer severe water shortages.

Linked to the more efficient use of water and water shortages is the introduction of water conservation measures. In weathered and fractured aquifers throughout India, shallow groundwater is widely used for small-scale irrigation and village potable supplies. Increasing abstraction from these low storage aquifers has resulted in severe seasonal water shortages in some areas. One response has been to put greater emphasis on water conservation schemes. Techniques include contour bunding, building check dams and constructing recharge ponds and tanks to reduce run-off and increase groundwater recharge. The cost of this work is usually met by the user community, government and non-governmental development organisations. The incentive for intervention is likely to be greatest where the value of the water resource is high because of scarcity or the type of use.

Although there are well-established economic methods of assigning value to water for human uses such as domestic supply, irrigation or industrial uses, it is particularly problematic to assign ecological and amenity value. Indirect measures of the environmental value and benefit of wetlands or a river flowing during the dry season can be measured in some attractive locations in terms of tourism revenues, but in most temperate locations groundwater additions to wetland and habitat diversity are ubiquitous and their loss could not be measured in such terms. Because it is difficult to agree a way of assigning a value to amenity and habitat conservation, historically these water uses have been under-prioritised for many catchments. Conversely, some wetland sites may be judged to be of international importance and may thus be considered to have a very high ‘value’. These assessments cannot easily be supported by economic justification and some moral judgement is required.

*References*
*Bibliography (pp.120-125) numbers 1, 2, 3, 6, 37, 47, 56, 66, 71, 84, 93, 96, 109 and 123 have been used in the production of this chapter.*

# FUNDAMENTALS OF POLLUTION

4

## SOURCES OF POLLUTION

There are many reports worldwide of groundwater becoming contaminated or at risk of contamination. What is meant by contamination? Water is in nature never pure but may contain dissolved minerals, micro-organisms, gases or suspended matter. Indeed, it is because water does contain these impurities that life on Earth is possible.

### BOX 13 POLLUTION AND CONTAMINATION

The terms **pollution** and **contamination** are sometimes used interchangeably in environmental matters to describe the introduction of a substance at a concentration sufficient to be offensive or harmful to human, animal or plant life. In this book, the word **pollution** is more strictly used to describe contamination caused or induced by human activities and typically measured by reference to predetermined permissible or recommended maximum limits.

Pollution of a body of water occurs when an impurity (micro-organism or chemical) is introduced by or as a result of human activities, creating an actual or potential danger to human health or the environment when present at high concentrations. Despite the perception that many people have of pollution being a modern phenomenon, it has occurred throughout most of human history, certainly since mankind ceased to be nomadic and started to make settlements. Water pollution occurred when humans began to farm the land and settle in villages and towns many thousands of years ago. For instance, the first clearing and ploughing of land for growing cereals will have released significant amounts of nitrogen from the soil into rivers, lakes and groundwater. Similarly, the sanitary disposal of domestic waste posed a problem for our ancestors in the earliest villages and towns, and bacterial contamination of soil and water must have been common.

Nevertheless, the scale and diversity of the three major human activities that may cause pollution (agriculture, urbanisation and industry) has increased rapidly in recent times (Figure 7).

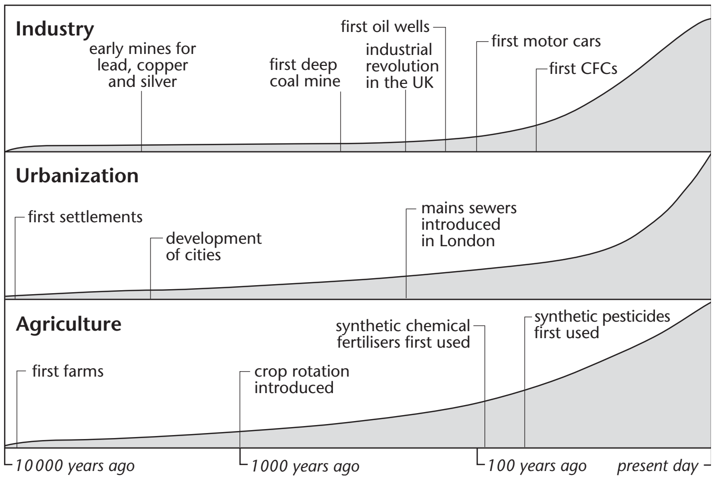



*Figure 7. Major human activities and how they have intensified through time.*

In most cases, contamination of groundwater by chemicals derived from urban and industrial activities, from modern agricultural practices and from waste disposal takes place almost imperceptibly. The slow movement of water from the surface through the unsaturated zone to deep aquifers means that it may be many years after a persistent chemical has entered the ground before it affects the quality of groundwater supplies.

Many human activities also generate a significant microbiological contaminant load at the land surface (for example, irrigation by waste water, intensive livestock raising and meat processing, on-site sanitation). In contrast to chemical contamination, the presence of microbiological contaminants indicates rapid movement to the water table from ground surface because most pathogenic micro-organisms have only limited persistence; bacteria for instance typically have survival times measured in days or months.

There are many reports of serious incidents resulting in contamination of groundwater supplies due to accidental spills, or unsatisfactory disposal of industrial chemicals. In addition solid and liquid waste generated by modern society is often spread over the land surface, and moisture from the waste and from rainfall may percolate down through the underlying soil. Depending on the type of waste, the resulting leachate may be highly acidic, have a large organic load or contain a high concentration of ammonia, toxic metals or various organic compounds, all of which may contaminate underlying groundwater.

In rural areas, there has also been concern for some years over the rise in nitrate concentrations in many groundwaters. There is no doubt that agricultural practices, including the heavy use of nitrogenous fertilisers that are an integral part of intensive arable farming, some cultivation regimes and intensive stock rearing have contributed directly to the rise. Direct discharges of nitrogen compounds from on-site sanitation and from sewer effluent also exacerbate the problem. The other area of concern lies with pesticide contamination; the extent of this remains unknown because of the very wide range of chemicals involved and the complexity of the decay processes, some of which may give rise to degradation products more toxic than the parent compound. Given the time lag between chemicals being applied to the soil and their arrival in water-supply wells, it is probable that contamination of groundwater supplies with nitrate and pesticides will continue and indeed increase during the coming years.

Spanning agriculture, industry and urbanisation is the diverse group of chemicals reported to disrupt the hormone system in humans, domesticated animals and wildlife. Endocrine (hormone) disruptors arise from many man-made processes (see Table 9) as well as occurring naturally. Poorly understood, their effects on human populations and on wildlife are the subject of much current research but their widespread occurrence at the land surface and the wide range of substance categories may make them a groundwater contaminant group of concern in the future.

**Table 9 Some categories of substances with reported endocrine-disrupting properties**

| Substance category | Examples | Uses | Reported modes of action |
|---|---|---|---|
| ***Naturally occuring*** | | | |
| Phytoestrogens | Isoflavones; Lignans; Coumestans | Present in plant material | Oestrogenic and anti-oestrogenic |
| Female sex hormones | 17-ß oestradiol; oestrone | Produced naturally in animals (including humans) | Oestrogenic |
| ***Man-made*** | | | |
| Polychlorinated organic compounds | Dioxins | Unwanted by-products from incineration and industrial processes | Anti-oestrogenic |
| | Polychlorinated biphenyls (PCBs) | No longer manufactured or used, but some equipment (mainly electrical) containing PCBs remains | |
| Organochlorine pesticides | DDT; dieldrin; lindane | Insecticides (some now banned phased out) | Oestrogenic and anti-or androgenic |
| Organotins | Tributyltin | Anti-fouling agent | |
| Alkylphenols | Nonylphenol | Used in production of nonylphenol ethoxylates and polymers | Oestrogenic |
| Alkylphenol ethoxylates | Nonylphenol ethoxylate | Surfactants | Oestrogenic |
| Phthalates | Dibutyl phthalate (DBP) Butylbenzyl phthalate (BBP) | Plasticisers | Oestrogenic |
| Bi-phenolic compounds | Bisphenol-A | Component in polycarbonate plastics and epoxy resins | Oestrogenic |
| Synthetic steroids | Ethinyl oestradiol | Contraceptives | Oestrogenic |

## ATTENUATION OF CONTAMINANTS IN THE SUBSURFACE

### SIGNIFICANCE OF THE UNSATURATED ZONE

As water moves through the ground, natural processes reduce (or attenuate) the concentration of many contaminants, including harmful micro-organisms. The degree to which attenuation occurs is dependent on the type of soil and rock, the types of contaminant and the associated activity. Attenuation is generally most effective in the unsaturated zone and in particular in the upper soil layers where biological activity is greatest. The soil layer represents the greatest opportunity for attenuation as both microbiological, and to a lesser extent key chemical contaminants, are removed, retarded or transformed by biological activity. The effectiveness of such processes has been recognised in recent years and been harnessed in numerous pollution cleanup projects using techniques known collectively as bioremediation. At deeper layers in the unsaturated zone attenuation still occurs, although the processes tend to be less effective as biological activity decreases. Once the saturated zone is reached, attenuation usually becomes far more limited and natural die-off and dilution predominate (Table 10).

**Table 10 Processes promoting contaminant attenuation in groundwater systems**

| | Dilution | Retardation | | | | Elimination | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *Sorption* | *Ion Exchange* | *Filtration* | *Precipitation* | *Hydrolysis* | *Complexation* | *Volatilization* | *Biodegradation* |
| **Soil** | Minor | Major | Significant | Major | Minor–significant | Significant–major | Major | Major | Major |
| **Unsaturated Zone** | Minor | Minor–significant | Significant | Significant | Significant | Significant | ? | Minor | Minor–significant |
| **Saturated Zone** | Major | Minor–significant | Minor–significant? | Significant | Minor–significant | Significant | ? | Minor | Minor–major |

*Major* *likely to produce a major reduction in concentrations for at least some contaminants.*
*?* *Process not well understood/documented*
*Significant* *likely to reduce concentrations for some contaminants significantly*
*Minor* *unlikely to reduce concentrations for any contaminant significantly*

The unsaturated zone is of special importance since it represents the first line of natural defence against groundwater pollution. Therefore, it is essential that it is considered fully in the evaluation of risks to groundwater supplies. Should the unsaturated zone be ignored, such evaluations will be excessively conservative. However, processes in the unsaturated zone can be complex, and its ability to attenuate contaminants difficult to predict.

Natural flow rates in the unsaturated zone of almost all soils do not generally exceed 0.2 m/d in the short term, and less when averaged over longer periods. However, the soil zone may be thin or absent and where the underlying geology consists of fractured rocks, water flow and pollutant penetration rates may be more than an order-of-magnitude higher, especially at high rates of infiltration (for example beneath septic tank drains). Thus, the presence of soil and its thickness, the grade of consolidation of strata, presence of fractures and the different rock types will be key factors in the assessment of aquifer pollution vulnerability, especially in relation to pathogens.

### SIGNIFICANCE OF THE SATURATED ZONE

Contaminant removal processes will, in the main, continue in the saturated zone of the aquifer but generally at much lower rates because groundwater moves more rapidly. Within the saturated zone, dispersion (spreading out of the contaminant plume) and dilution will play an important role in reducing contaminant concentrations although it is not a reliable reduction mechanism for highly toxic contaminants.

Nevertheless, for low-yielding boreholes (for example those fitted with a handpump) in intergranular aquifers, the travel time for water to move downward from the water table to the intake of the borehole can be considerable even for quite small vertical distances. Such travel times, whilst they would only delay the arrival of persistent contaminants, will substantially reduce the hazard from less persistent contaminants (including many micro-organisms) arriving at the water supply.

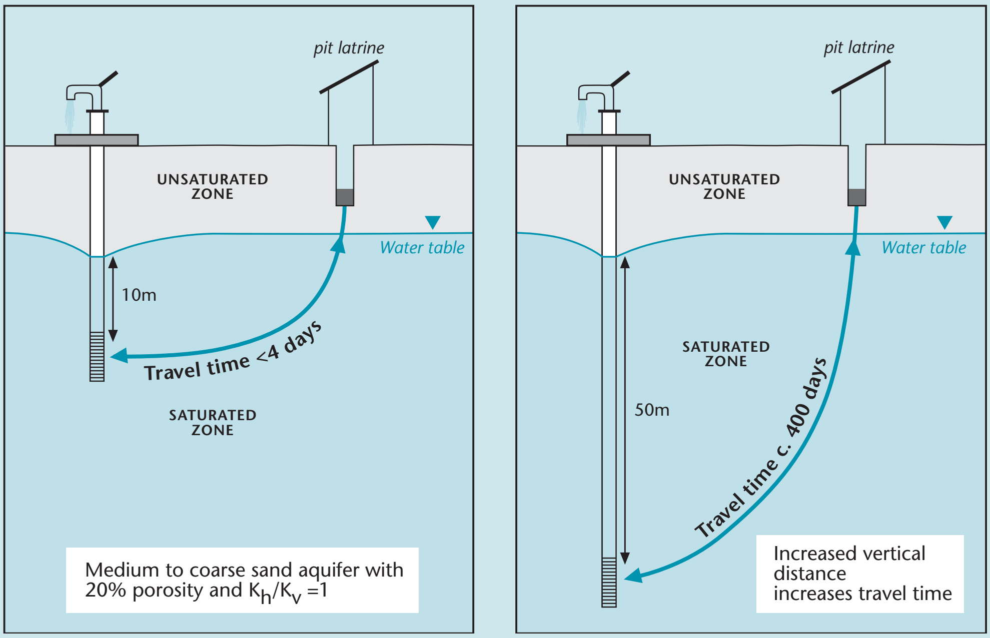
**BOX 14 ASSESSING RISK TO DRINKING WATER SUPPLY FROM ON-SITE SANITATION; DESIGNING SEPARATION DISTANCE USING A PATHOGEN ATTENUATION CRITERION**

The generally accepted minimum separation for pollution source and groundwater supply in western Europe is equivalent to 50 days travel time. This is based on survival times of faecal indicator bacteria and viruses from laboratory and field experiments. In recognition of separation distance realities in the developing world, the ARGOSS risk assessment guidelines for on-site sanitation (ARGOSS, 2001) define three levels of risk:

| | |
|---|---|
| *Significant risk* | less than 25 days travel time |
| *Low risk* | 25 to 50 days travel time |
| *Very low risk* | more than 50 days travel time |

The *Low risk* category provides confidence, but there is no guarantee that the travel time between contaminant source and supply would result in numbers of micro-organisms which are unlikely to pose a major risk to health. The *Very low risk* category provides a further margin of safety, although as routine monitoring rarely analyses for particular pathogens, confirmation is not normally possible.

The travel time for flow to a borehole screen can be calculated for different pumping rates, screen depths, effective porosities and permeability anisotropy (kh/kv) ratios using the Darcy formula. This enables separation distances to be calculated that would provide a travel time sufficient to reduce the risk to a *Low* or *Very low* status. The diagram shows the results for two borehole designs in the same shallow water-table aquifer; the separation distance for the shallow design would be unacceptable because the travel time is only a few days, and a design with a deeper screen would be required.




*Example of effect of borehole design on travel time and pathogen attenuation efficiency where on-site sanitation is practised*

## ATTENUATION OF MICROBIOLOGICAL CONTAMINANTS

The key processes in the attenuation of microbiological contaminants are:

- die-off and predation;
- filtration;
- adsorption;
- dilution/dispersion.

Micro-organisms, like all life forms, have a limited life span. Their die-off rates are measured by the half-life (the time taken for a 50 per cent reduction in numbers) and vary enormously from a few hours up to many months. A variety of factors influence the survival of a particular microbe (Figure 8).

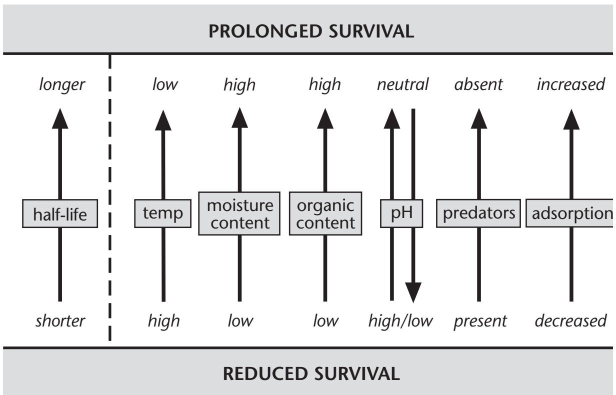



*Figure 8. Factors affecting microbe survival and half-life (from Coombs el at., 1999).*

In groundwater, some viruses are known to survive for up to 150 days and encysted protozoa even longer. In the case of indicator bacteria (microbes commonly associated with pathogens but more easily incubated and identified), a half-life in low-temperature groundwater can be as high as 22 days, with survival of appreciable numbers up to 32 days.

Other key processes in microbiological attenuation are adsorption and filtration. In the first case, micro-organisms become attached to particles in the subsurface, thus effectively removing them from water infiltrating into the soil. The ability of micro-organisms to be adsorbed depends on the nature of the organisms, the pH (acidity) of the water and the type of unsaturated zone material. Under natural pH conditions microbes suspended in water have a net negative electrostatic charge, as do most mineral surfaces, and so remain mobile. Under certain conditions, for example acidic groundwater and in the presence of reactive clay minerals, the surface charge may reverse and adsorption occur. This is a reversible process, and viruses for example can be de-sorbed (or eluted) when flows and pH alter, especially during recharge periods. Chemical adsorption effects can also occur, especially with viruses.

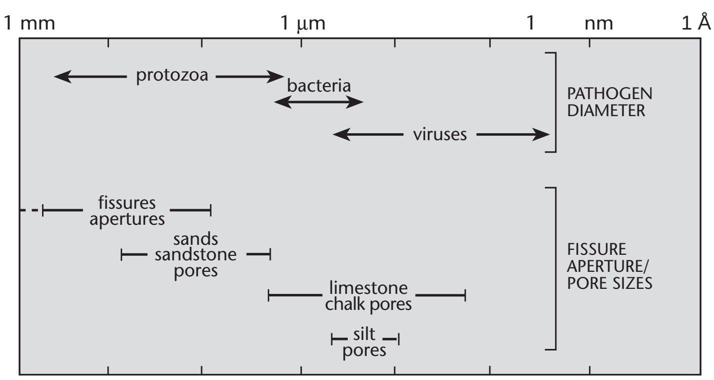
Mechanical filtration is more effective for larger organisms such as protozoan cysts, but will also help to attenuate bacteria. The effect is dependent on the pore size of the rock (Figure 9) but microbe shape can also be significant. Bacteria, especially, are very variable in form, ranging from spherical to rod-shaped to filamentous, and the ease of movement will be influenced by their geometric shape. Filtration can be effective in retarding larger micro-organisms, but it should be noted that this does not inactivate the organisms.

Dispersion, caused by the tortuous route taken by water flowing through the rock material, has the effect of spreading contaminant plumes, diluting the ‘concentration’ at any point and increasing the range of time that contaminants take to flow from source to groundwater supply.

The effect of dispersion/dilution on micro-organisms is less easy to quantify than for chemicals, given the discrete nature of microbes in water and the observed phenomenon that micro-organisms are often found to clump together.

Contamination of groundwater can also occur as a consequence of poor design and construction of the borehole, well or spring supply. For instance, in a borehole, failure to provide a proper sanitary seal between the well casing and the ground can provide a ready and rapid pathway for contaminants to migrate from the land surface close to the well-head down casing annulus to the water table. Such pathways rapidly bypass the unsaturated zone and provide little opportunity for contaminant alteration.

*Figure 9. Pathogen diameters compared with aquifer matrix apertures.*



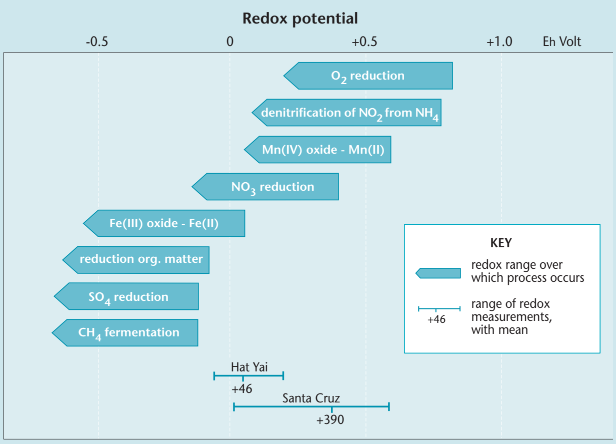
## BOX 15 SECONDARY WATER QUALITY CHANGES

Secondary water quality changes are an effect only recently recognised in aquifers underlying cities or large industrial complexes. These are caused by a combination of the increased contaminant load at the urban land surface/shallow subsurface and its penetration as city boreholes induce downward leakage of urban recharge. Both the industrial and the domestic components of urban waste water have a high organic content. This organic content is relatively easily oxidised under aerobic conditions and where the water table is deep, oxygen and micro-organisms in the unsaturated zone of the aquifer may remove (degrade) much of the organic content.

Below the water table, any further degradation (of organic matter) will consume the dissolved oxygen present in the groundwater:

$$CH_2O + O_2 = CO_2 + H_2O$$
$$CO_2 + H_2O = HCO_3^- + H^+$$

Oxygen in this reaction is termed the electron acceptor. The quantity of oxygen dissolved in groundwater is much less than that present in the unsaturated zone and is less rapidly replaced. Thus depletion of dissolved oxygen is possible whenever the oxygen demand for the degradation of organic matter exceeds supply. When this happens the oxidation-reduction (or redox) potential of the groundwater declines and further degradation of organic matter continues utilising other ions (electron acceptors) that are progressively more difficult to reduce. These include, in order of disappearance, nitrate ($NO_3^-$), ammonium ($NH_4$–), manganese ($Mn^{4+}$), ferric iron ($Fe^{3+}$), and sulphate ($SO_4^{2-}$) (see figure). These compounds often occur naturally either in the mineral grains of a rock or in the cement that binds the grains together. Significant water quality changes result which, depending on the aquifer setting, can be adverse (leading for instance to increases in the dissolved metals content in pumped groundwater) or beneficial (as denitrification can reduce otherwise unacceptable nitrate concentrations). Box 16 describes these effects studied in the two cities of Santa Cruz Bolivia and Hat Yai Thailand, but the process is likely to be much more widespread in susceptible aquifer settings. A similar set of reactions for instance often occurs around municipal refuse disposal sites and beneath farm waste slurry pits.




*Sequence of microbially mediated redox processes*

High iron and manganese concentrations, although not a threat to health, do represent a water quality problem, as they may be unacceptable for domestic purposes (because they impart an unpleasant taste and can stain laundry) and for some industrial processes. Removal of these ions by treatment is expensive. A more serious concern in health terms is the presence of naturally occurring arsenic in some rock formations, apparently associated with iron oxide minerals. Concentrations in excess of 20 times the WHO guidelines have been observed in shallow groundwater as arsenic is mobilised under changed redox conditions, caused by seepage to the ground of urban effluent containing a high organic load. Mobilisation of arsenic in deeper aquifers has also been confirmed. The implications are serious firstly because of the health implications of excess arsenic in drinking water and secondly because arsenic is a relatively abundant element in alluvial sediments. The mobilisation of arsenic by iron oxide dissolution could occur more generally beneath unsewered cities and therefore urban groundwaters need to be monitored for arsenic especially where strongly reducing conditions prevail such as those produced by the disposal of waste water to the subsurface. The presence of high concentrations of dissolved iron and manganese and of low concentrations of nitrate and sulphate in groundwater is indicative of reducing conditions.

As the volume of water migrating by this route to the water table is usually small in comparison with that entering the borehole screen from the aquifer, the quality problems that develop are normally microbiological rather than chemical. This is because dilution within the borehole normally reduces any chemical contaminants to acceptable concentrations, whereas even low microbiological counts can represent a significant and unacceptable hazard.

## ATTENUATION OF CHEMICAL CONTAMINANTS

In the unsaturated zone water movement is normally slow and the chemical condition is commonly aerobic and pH neutral. This provides potential for:

- attenuation of heavy metals and other inorganic chemicals, through precipitation (as carbonates, sulphides or hydroxides), sorption or ion exchange;
- sorption and biodegradation of many natural and synthetic hydrocarbon compounds.

However, in the case of persistent, mobile pollutants, the unsaturated zone merely introduces a large time lag before arrival at the water table, without any beneficial attenuation. In many other cases the degree of attenuation will be highly dependent upon the flow regime and residence time.

An additional consideration is the geochemical response of the aquifer to the contaminant load imposed on it. Marked changes in the behaviour of certain contaminants occur if the polluting activity has sufficient organic or acidic load to bring about an overall change in the reduction/oxidation potential (redox) or pH. An example of this is the denitrification process, which occurs in reducing conditions and has the ability to remove nitrogen by volatilisation (see Box 16). Processes in the underlying saturated zone of aquifers are similar but generally occur at much lower rates. Reduction of pollutant concentrations below the water table will depend primarily on dilution, resulting from hydrodynamic dispersion, which will not be a reliable control for highly toxic contaminants. Moreover, secondary water quality changes can occur, in which elements naturally present in the aquifer matrix (but not dissolved in groundwater) become more soluble. This can be a concern beneath urban and industrial agglomerations, where diffuse contaminant loads can be sufficient to change the geochemical status of the aquifer (Boxes 15; 16; 17).

The physical characteristics of the contaminant also affect mobility and likely persistence. This can be best illustrated by comparing the two main classes of synthetic hydrocarbon compounds. Aromatic types such as diesel, fuel or lubricating oils or other LNAPLS* are of low density and a spillage would tend to float on top of the saturated aquifer. Some aromatic compounds are also relatively viscous and so less mobile at typical groundwater temperatures. In contrast an important group of halogenated aliphatic compounds, widely used as solvents (DNAPLs)**, are both dense and of low viscosity. These highly toxic compounds descend to the base of the aquifer in the immiscible phase. As the solvent sinks through the aquifer, some of the immiscible phase will be left behind in the pores and fractures. This residual will slowly dissolve, producing a plume that extends through the full aquifer thickness and migrates down gradient. (Figure 10). A particularly pernicious feature of the latter is that they are also microbiologically toxic, so that natural or enhanced bioremediation is much more protracted and complex than in the case of many common aromatic hydrocarbons.

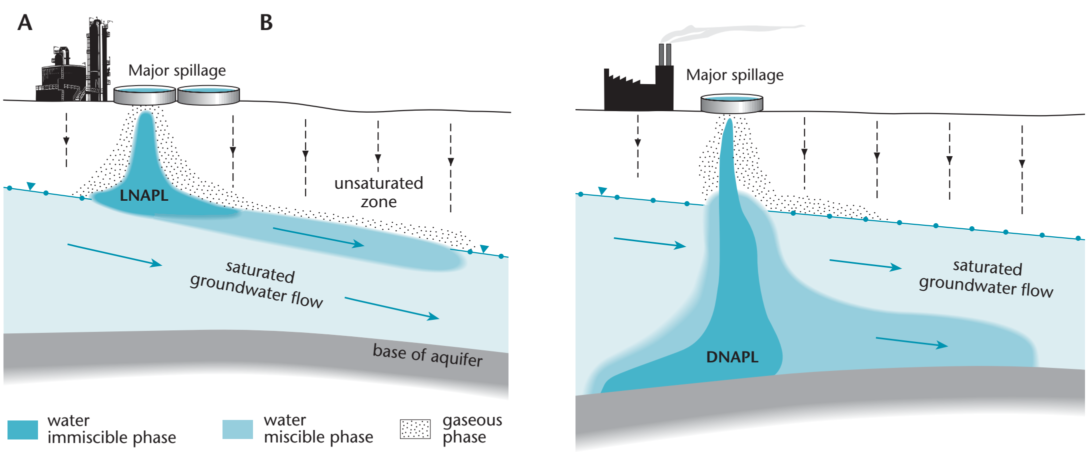



*Figure 10. Subsurface distribution of (A) aromatic low-density and (B) halogenated high-density hydrocarbons following a major surface spillage (modified from Lawrence and Foster, 1987).*



* LNAPL: Light non-aqueous phase liquid, for example petroleum derivatives like diesel, kerosene, fuel and lubricating oils
** DNAPL: Dense non-aqueous phase liquid, for example Tetrachloromethane; 1,1,1-trichloroethane; tetrachloroethene; trichloroethene

## BOX 16 SECONDARY WATER QUALITY CHANGES IN URBAN AQUIFERS

Secondary water quality changes are illustrated by the effects of waste-water infiltration below the cities of Hat Yai in Thailand and Santa Cruz in Bolivia where on-site waste-water disposal has been widespread. The constituents of waste water in aquifers react with each other, with subsurface gases and with the porous medium of the aquifer matrix itself. Most geochemical changes in waste water occur as a result of the reactions of a few major components that, in turn, affect redox potential and pH, the master variables of aquifer geochemistry. For example, nitrogen present in organic form in infiltrating waste water can be transformed and volatilised as it undergoes bacterially mediated processes but only under certain circumstances.

Across much of the city centre in **Santa Cruz**, organic nitrogen entering the shallow aquifer has been oxidised via ammonium on its passage through the oxygen-rich unsaturated zone. It reaches the aquifer relatively unattenuated, mainly as nitrate. The conversion of ammonium to nitrate generates acidity, which, in the case of Santa Cruz, is buffered by the calcium carbonate present in the rock matrix, and so little or no change in pH is detected. At a few sites where oxygen has been fully consumed in the breakdown of organic carbon, denitrification occurs and a proportion of the nitrogenous leachate is converted to nitrogen gas (see Figure A). This mitigating effect only occurs however where the loadings are so high that the system has become anaerobic, so although the nitrate content in the saturated aquifer is significantly reduced, it may still be higher than is acceptable according to water quality norms.

These changes in the forms of compounds present in groundwater can convert chemicals from nontoxic to toxic forms, and vice versa; for example, the change from the potentially toxic nitrate and nitrite to nitrogen gas. Making an aquifer more reducing can either increase the solubility of toxic compounds (arsenic, manganese) or reduce them (nitrate, chromium, selenium). It can also increase the dissolved iron and manganese content, making the water unacceptable for some purposes.

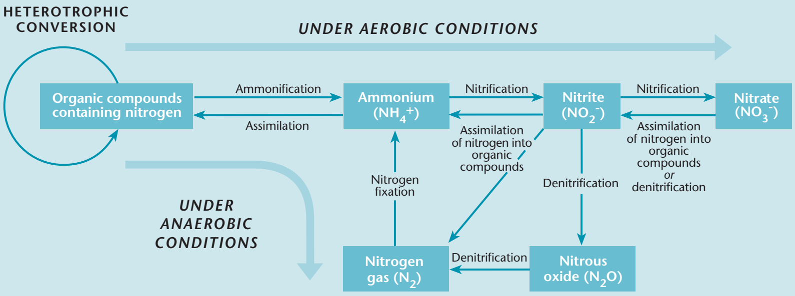



*Figure A Transformations of nitrogen from waste water during groundwater recharge (from Lawrence et al., 1997)*

In Hat Yai the groundwater system has become more reducing than in Santa Cruz, due in part to the very shallow water table. Little carbonate is present in the rock matrix, so during oxidation of the ammonia the tendency is for the pH to fall. At a lower pH, heavy metals have a greater mobility and are more likely to go into solution. In the city centre, the nitrate has been entirely consumed and naturally occurring micro-organisms are likely to utilise manganese or iron present in the rock matrix (or sulphate in urban recharge) to break down organic food sources. This increases the concentrations of manganese and iron in solution as they are more soluble in their reduced form (an effect also observed in the centre of Santa Cruz). In addition, any naturally occurring arsenic, which may be loosely bound to iron oxide in the matrix or on grain surfaces, is also released into the groundwater. Concentrations up to 1.0 mg/l arsenic were found in the most reducing zones of the aquifer and, in general, high arsenic and iron concentrations were found to be associated in Hat Yai (Figure B).

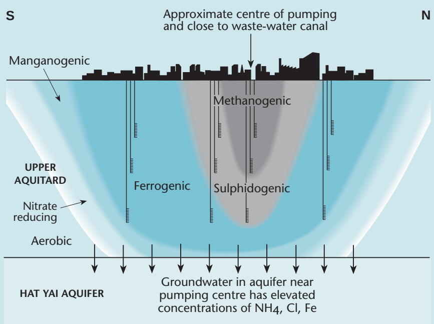


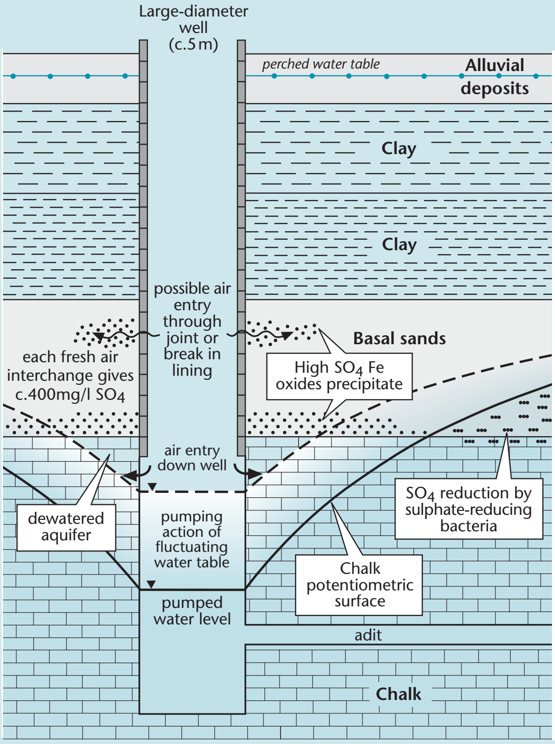

*Figure B Cross-section through Hat Yai showing redox zones*

This lowland alluvial aquifer setting is common throughout much of southern Asia, and an example from a water quality study in the densely populated marginal housing area of Dattapara north of Dhaka city in Bangladesh shows how the impact of heavy nitrogen loading from pit latrines on shallow groundwater can be self-mitigated in these conditions of shallow water table and poorly permeable clay soils. The very high population density (about 620 persons/ha) generates a high nitrogen loading estimated at 3000 kg N/ha/annum yet nitrate concentrations in shallow domestic supply tubewells, 10 to 20 m deep, were surprisingly low at less than 20 per cent of the WHO guideline of 11.3 mg/l $NO_3$-N. Anaerobic conditions (evidenced by negligible dissolved oxygen and redox potential of –250 mV) favour denitrification and the formation of ammonium, which is either volatilised to the atmosphere as ammonia, sorbed to sediments or remains in solution.

## BOX 17 PYRITE OXIDATION IN 'REDUCING' AQUIFERS

Sometimes the effects of pollution can be indirect and unsuspected. The most dramatic effects relate to redox effects. The potential secondary effects arising from on-site waste-water disposal in the cities of Hat Yai, Thailand and Santa Cruz, Bolivia were illustrated in Box 16. These illustrated the impact of making the aquifer more reducing but the reverse can also occur. Entry of oxidants, principally oxygen and nitrate, into previously reducing aquifers can also have serious repercussions on groundwater quality. This occurs most commonly in sandy alluvial aquifers containing pyrite ($FeS_2$), a common minor mineral that can occur where such aquifers are overlain by a confining layer of silt or clay. For example, excess fertiliser nitrate infiltrating into sandy alluvial aquifers in Germany has led to excessive concentrations of sulphate in groundwater. Although dissolved oxygen can also oxidise pyrite, the limited solubility of oxygen (about 8–10 mg/l for the typical range of groundwater temperatures) means that the amount of pyrite able to be oxidised in this way is relatively small. Much larger quantities can be oxidised when air is allowed to enter the aquifer. This results most frequently when the water table is lowered following extensive groundwater abstraction. A large quantity of sulphate then accumulates in the unsaturated zone, where it is relatively immobile, and is only detected in pumped groundwater when the regional rate of abstraction is reduced and the water table rises.

Such an effect has been found in north London, where a succession of sand and clay overlies and confines the nationally important Chalk aquifer. Following proposals to develop the aquifer for artificial recharge, pilot investigations found poor quality abstracted water following recharge. In some areas, the Chalk water level oscillates around the top of the aquifer due to seasonal changes and to cycles of pumping and non-pumping. The resultant saturation and drainage pulses air through the pyrite-bearing sandy beds overlying the Chalk, and the resulting oxidation has produced porewater concentrations of up to 30 000 mg/l sulphate in the sandy beds. Leakage from these sands can produce sulphate concentrations in excess of the WHO guideline value of 250 mg/l in water pumped from the underlying Chalk (see figure).




*Schematic diagram showing how localised oxidation and reduction could occur around a large-diameter well, north London artificial recharge scheme (after Kinniburgh et al., 1994).*

Pyrite oxidation also releases large amounts of acidity and the groundwater may become quite acid where the aquifer has no minerals, such as calcite ($CaCO_3$), which can be readily weathered to neutralise the acidity. This reaches an extreme situation in many mines where the drainage water can be extremely acidic. Acid mine drainage can also contain high concentrations of iron, zinc, lead, arsenic and other trace constituents which either arise directly from the dissolution of pyrite or indirectly from the dissolution of other minerals as a result of the acidity produced. Unlike the protection measures employed in traditional aquifers, for example nitrate protection zones or restrictions on the siting of on-site sanitation, aquifer protection measures in reducing aquifers involve maintaining as a high a water table as possible in order to prevent air entry and oxidation.

## POLLUTION RISK AND AQUIFER VULNERABILITY

### SIGNIFICANCE OF DIFFERENT GROUNDWATER SETTINGS TO GROUNDWATER VULNERABILITY

The eight hydrogeological environments described in Chapter 2 differ greatly in the time taken for recharge entering at the land surface to reach the water table of the aquifer. At the regional or national level, a very general assessment of aquifer vulnerability could use the typical travel times of its hydrogeological environment as a rough guide to the relative degree of hydraulic inaccessibility of the aquifer system (Table 11).

**Table 11 Hydrogeological settings and their associated groundwater pollution vulnerability**

| Hydrogeological setting and aquifer type | | Typical travel times to water-table | Attenuation potential of aquifer | Pollution vulnerability |
|---|---|---|---|---|
| Major alluvial and coastal plain sediments | Unconfined<br>Semiconfined | Weeks–months<br>Years–decades | Moderate<br>High | Moderate<br>Low |
| Intermontane valley-fill and volcanic systems | Unconfined<br>Semiconfined | Months–years<br>Years–decades | Moderate<br>Moderate | Moderate<br>Moderate–low |
| Glacial and minor alluvial deposits | Unconfined | Weeks–years | Moderate–low | High–moderate |
| Loessic plateaux | Unconfined | Weeks–months | Low–moderate | Moderate–high |
| Consolidated sedimentary aquifers | Porous sandstone<br>Karstic limestone | Weeks–years<br>Days–weeks | Moderate<br>Low | Moderate-High<br>Extreme |
| Coastal limestones | Unconfined | Days–weeks | Low–moderate | High–extreme |
| Extensive volcanics | Lava<br>Ash/Lava sequences | Days–months<br>Months–years | Low<br>High | High–extreme<br>Low |
| Weathered basement | Unconfined<br>Semiconfined | Days–weeks<br>Weeks–years | Low<br>Moderate | High–extreme<br>Moderate |

Unsaturated zone travel time and aquifer residence time are important factors in any aquifer assessment because they affect the ability of the aquifer to eliminate or mitigate contamination from activities at the land surface. For instance, a residence period of a month or so is adequate to eliminate most bacterial pathogens. Spillages of more intractable contaminants such as petrol or other fuels can, given time, undergo significant degradation in *situ* by the indigenous microbial population of the rock, and this process can be stimulated in some aquifer settings by selective use of site-specific auto-remediation techniques such as aeration and nutrient addition.

Even if the contaminant is not easily degraded, so that the total quantity reaching the groundwater resource is not greatly reduced, some aquifer systems are better able to mitigate the effects of groundwater quality degradation than others. For example, the saturated zone of an aquifer with high storage capacity holds much water that could dilute contaminant concentrations to acceptable limits. Other systems with dual permeability may be capable of attenuating contaminant peaks by diffusion from water flowing through the fractures into the relatively immobile interstitial water in the aquifer matrix (Figure 11).

The rate of diffusion depends in part on the concentration gradient and also on the type of porosity. Diffusion occurs even when there is no groundwater flow and although slow, this is a property that is especially important where the porosity is high, as pollutants can move into (and out of) the matrix even when there is little or no flow through large pores or fractures. This can be an advantage, as the process will tend, with time, to average out the concentration of contaminant throughout the aquifer. Conversely, it can make it technically very difficult to purge an aquifer of a persistent and undesirable pollutant, because the solute may enter zones through which flow is negligible, such as small pores and narrow pore throats in intergranular-flow aquifers or microfractures with very small apertures in fracture-flow aquifers systems.

Because of the diffusion effect, pollution can continue for a very long time before it is noticed, for example at seepages, and thus there may be a delay in dealing with a spill/leak, or a false assumption that is has not created a problem.

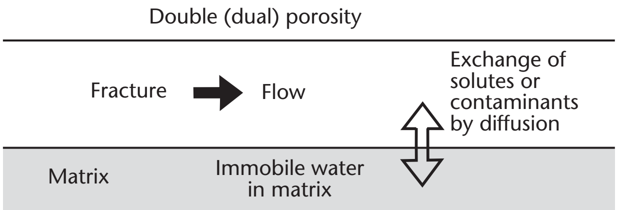



*Figure 11. Schematic representation of double porosity aquifer.*

## USING AQUIFER VULNERABILITY TO ASSESS POLLUTION RISK

Groundwater pollution risk can be illustrated as the interaction between two semi-independent factors:

- the contaminant load that is applied to the subsurface environment as a result of human activity;
- the natural pollution vulnerability of the aquifer.

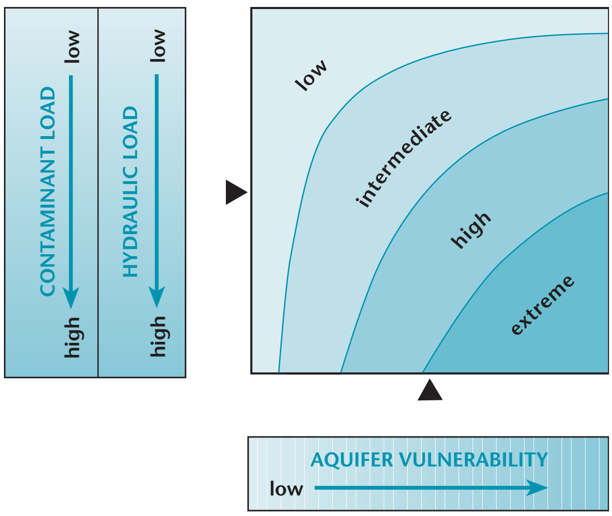



*Figure 12. Conceptual scheme of groundwater pollution risk.*

Within this scheme (Figure 12), it is possible to have high vulnerability but no pollution risk, because of the absence of significant contaminant load, and vice versa. Both are perfectly consistent in practice. Moreover, the contaminant load can be controlled or modified but not the aquifer vulnerability.

The term *aquifer pollution vulnerability* is used to represent the intrinsic characteristics of the aquifer that determine whether it is likely to be affected by an imposed contaminant load. Vulnerability assessment is based on the potential contaminant attenuation capacity from surface to the water table (or to the aquifer in the case of semiconfined groundwater systems). Aquifer vulnerability can be subdivided into four broad classes (Table 12).

**Table 12 Definition of aquifer vulnerability classes**

| Vulnerability class | Definition |
|---|---|
| Extreme | Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios |
| High | Vulnerable to many pollutants except those highly adsorbed or readily transformed |
| Low | Only vulnerable to the most persistent pollutants in the very long-term |
| Negligible | Confining beds present with no significant groundwater flow across them |

Extreme vulnerabilities are associated with highly fractured aquifers with a shallow water table as they offer little chance for contaminant attenuation. However all aquifers are vulnerable to persistent contaminants derived from a widespread polluting activity. Aquifer vulnerability can be depicted on maps that show areas of similar susceptibility (Figure 13) and can be produced as part of a national programme to protect major aquifer systems or for assessing local groundwater control needs (Box 18).

Such maps are based on background information on the aquifer characteristics (depth to water, presence of shallow aquitard, permeability, degree of fracturing etc) and are a useful planning tool, particularly for siting new activities that are potentially prejudicial to groundwater.

Other considerations that will determine whether the risk of aquifer pollution will result in serious threat to

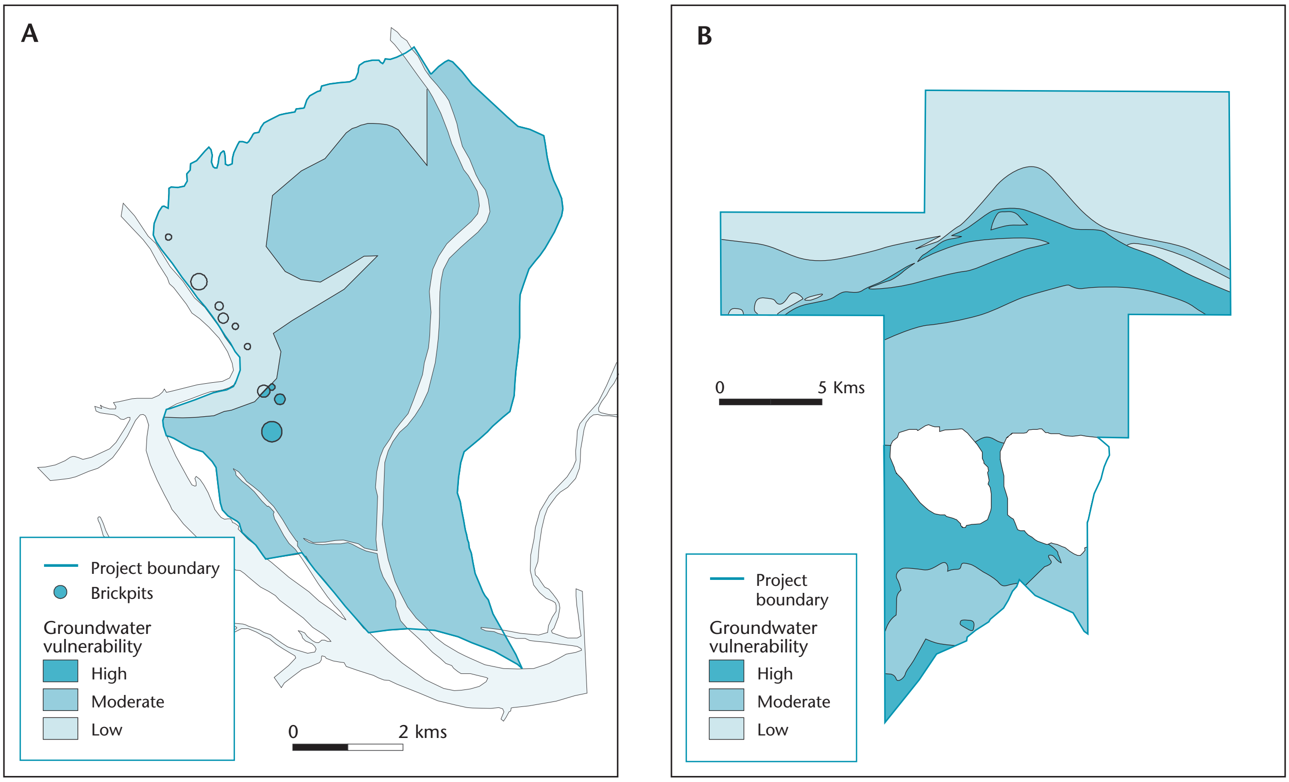



*Figure 13. Examples of urban groundwater vulnerability maps; the cities of (A) Narayanganj, Bangladesh and (B) Bishkek, Kyrghyzstan.*

the quality of groundwater already developed or designated for water supply include:

- mobility and lateral transport of contaminants within the aquifer and the position of the pollution source relative to the groundwater abstraction site;
- magnitude of the pollution episode;
- design and construction of the well;
- value of the groundwater resources.

## SUBSURFACE CONTAMINANT LOAD

### LOAD CHARACTERISATION

The other element of groundwater contaminant hazard identification is the subsurface load, precise information on which will allow more accurate evaluation of the extent of risk. The principal aims of risk assessments are either predictive or preventative:

- to predict the likely severity and extent of contamination not yet fully experienced in water drawn from the aquifer;
- to prevent contamination by putting in place measures to control the more hazardous components of the load;
- to reduce risk or limit contamination severity.

While a wide range of human activities are likely to generate some contaminant load, it is often found that just a few are responsible for the major groundwater pollution hazard in a given area.

Inadequate characterisation of the subsurface contaminant load also greatly impedes a detailed investigation of major groundwater pollution episodes and the prediction of future groundwater quality trends resulting from such episodes. The so-called input factor (the amount of contaminant and the duration of application) is almost invariably one of the most poorly defined factors in groundwater pollution evaluation and modelling.

A comprehensive list of activities that potentially can generate a subsurface contaminant load is presented and classified (Table 13). Some of the activities causing serious pollution risk in developing economies are comparable to those present in the highly industrialised nations, but some of those presenting the most serious threat differ significantly, both individually and collectively, from their counterparts elsewhere.

**Table 13 Summary of activities that could potentially generate a subsurface contaminant load (adapted from Chilton in Chapman, 1996)**

| | Character of pollution load | | | | |
|---|---|---|---|---|---|
| Activity/structure | Distribution | Category | Main types of pollutant | Relative hydraulic surcharge | Soil zone by-passed? |
| **Urban waste water and other services** | | | | | |
| Unsewered sanitation | ur | P-D | *pno* | + | ✓ |
| Land discharge of sewage | ur | P-D | *nsop* | + | |
| Stream discharge of sewage | ur | P-L | *nop* | ++ | ✓ |
| Sewage oxidation lagoons | ur | P | *opn* | ++ | ✓ |
| Sewer leakage | ur | P-L | *opn* | + | ✓ |
| Landfill/solid waste disposal | ur | P | *osnh* | | ✓ |
| Highway drainage soakaways | ur | P-L | *soh* | ++ | ✓ |
| Wellhead contamination | ur | P | *pn* | | ✓ |
| **Industrial development** | | | | | |
| Process water/effluent lagoons | u | P | *ohs* | ++ | ✓ |
| Tank and pipeline leakage | u | P | *oh* | + | ✓ |
| Accidental spillages | ur | P | *oh* | ++ | |
| Land discharge of effluent | u | P-D | *ohs* | | |
| Stream discharge of effluent | u | P-L | *ohs* | ++ | ✓ |
| Landfill disposal residues and waste | ur | P | *ohs* | | ✓ |
| Well disposal of effluent | u | P | *ohs* | ++ | ✓ |
| Aerial fallout | ur | D | *a* | | |
| **Agricultural development** | | | | | |
| *Cultivation with:* | | | | | |
| Agrochemicals | ru | D | *no* | | |
| Irrigation | r | D | *sno* | + | |
| Sludge and slurry | r | D | *nos* | | |
| Waste water irrigation | r | D | *nosp* | + | |
| *Livestock rearing/crop processing* | | | | | |
| Unlined effluent lagoons | r | P | *pno* | + | ✓ |
| Land discharge of effluent | r | P-D | *nsop* | + | ✓ |
| Stream discharge of effluent | r | P-L | *onp* | + | ✓ |
| **Mining Development** | | | | | |
| Mine drainage discharge | ru | P-L | *sha* | ++ | ✓ |
| Process water/sludge lagoons | ru | P | *has* | ++ | ✓ |
| Solid mine tailings | ru | P | *has* | | ✓ |
| Oilfield brine disposal | r | P | *s* | + | ✓ |
| Hydraulic distrubance | ru | D | *s* | | NA |
| **Groundwater resource management** | | | | | |
| Saline intrusion | ur | D-L | *s* | | NA |
| Recovering water levels | u | D | *soa* | | NA |

*Distribution: u urban/industrialised zones r rural*
*Category: P point D diffuse L linear*
*Types of pollutant: p faecal pathogens n nutrients o organic micropollutants h heavy metals s salinity a acidification*
*Relative hydraulic surcharge: + to ++ increasing importance, relative volume or impact of water entering with pollution load*

The differentiation between pollution from readily identifiable point or line sources, and diffuse pollution, is fundamental because it determines the likely extent and magnitude of contaminant loading. Similarly, in consideration of pollution prevention and control measures it is important to distinguish between those activities in which the generation of a subsurface contaminant load is an integral design feature, and activities in which it is an incidental or accidental component.

Whilst detailed characterisation of the subsurface load is often difficult to achieve, a broad classification is usually possible. Four characteristics need to be considered.

### CLASS OF CONTAMINANTS

Mobility and persistence are the two key properties of a contaminant in respect of its potential to contaminate groundwater. Mobility refers to the ease with which the contaminant is leached to the water table. Non-mobile compounds tend to be retained in the soil as a result of sorption, cation exchange, or precipitation processes. Some compounds may be mobile but are impersistent and degrade rapidly to simpler, generally nontoxic, compounds.

### INTENSITY OF CONTAMINATION

As the intensity of contaminant loading to the subsurface increases, so the potential for groundwater contamination increases. It is generally considered that at low intensities of application, the soil zone is able effectively to eliminate and attenuate many contaminants, but that above a certain critical threshold a progressively greater percentage of the contaminant will be leached.

### MODE OF DISPOSITION

The mode of disposition refers to both the areal extent and where within the saturated–unsaturated profile the application is made. Diffuse or multipoint pollution sources produce widespread contamination of generally lower concentration. Conversely, point source pollution produces localised contamination often of high concentration.

The soil layer is generally the most effective layer in attenuating contaminants. Thus, contaminants that bypass this layer (for example seepage from soakaways, drains and solid waste disposal pits or from leaking underground tanks) may pose a more serious threat to groundwater than those contaminants applied directly to the soil surface (for example agricultural chemicals).

### DURATION OF APPLICATION

The duration of the contamination episode is also important. The release of contaminants into the aquifer over a short period may be effectively dispersed and diluted during migration through the saturated zone, particularly in the deeper groundwater systems. Important exceptions will arise where the contaminants are especially toxic (for example chlorinated solvents, some heavy metals, radioactive wastes) such that even small quantities can cause serious groundwater pollution.

## GROUNDWATER POLLUTION RISK ASSESSMENT

### PROTECTING GROUNDWATER: TECHNICAL AND INSTITUTIONAL CONSTRAINTS

The concept of pollution risk as the interaction between aquifer vulnerability and the contaminant load is both important and useful. It enables a relatively quick assessment of pollution risk to be made, based on background information on both the aquifer characteristics (depth to water, permeability, degree of fracturing, etc) and the polluting activities (class of contaminant, duration and intensity of application and disposition). This type of information may be relatively easy to obtain from existing data, and may be combined with supplementary surveys. The risk assessments can be used to identify groundwater environments, most contamination and areas where monitoring is most urgently required to evaluate the scale and extent of a groundwater quality problem if one exists (Box 18).

Given the importance of groundwater for both potable water supplies and for irrigation worldwide and the limited quantity of fresh water available in many countries it may be thought that protecting groundwater quality would be a priority issue when planning urban/industrial development or other significant land-use changes.

Unfortunately, this is usually not the case and it raises the question why this should be so. In many countries, ownership of the water is often unclear due to ambiguous legal status and regulation is accordingly weak. Furthermore, agencies responsible for protecting and evaluating groundwater resources, where they exist, often have limited powers and even more limited resources.

The production of aquifer vulnerability maps is rarely undertaken, but this is a very useful first step in assessing groundwater pollution risk at the planning

## BOX 18 VULNERABILITY OF URBAN AQUIFERS: ASSESSMENT EXAMPLES FROM DEVELOPING CITIES IN BANGLADESH AND KYRGHYZSTAN

**Narayanganj** is a small groundwater-dependent city of about one million people in central Bangladesh. It is a textile manufacturing centre, with factories undertaking all stages of production from spinning, dyeing, bleaching, weaving and proofing through to the making of garments and other finished cloth products. Other industries include soap-making, metal re-rolling and metal and wood furniture manufacture. The city had a high estimated annual population growth rate of 5.8 per cent per annum during the 1990s. Narayanganj is underlain by a thick unconsolidated alluvial multi-aquifer system with complex lateral interdigitation of medium- to coarse-grained sands and fine-grained sand, silt and clay. The top 150 m is utilised principally for public and industrial supply purposes, but the shallow aquifer is an important resource with many domestic and community handpump tubewells of less than less than 40 m deep.

**Bishkek** (population about 800 000) lies on the northern flanks of the Tien Shan mountains in northern Kyrghyzstan. It is the capital and main industrial centre, and is 100 per cent dependent on its aquifer system for potable, domestic, industrial and district heating water supplies, provided by both intra-urban and peri-urban well fields. The city overlies a thick laterally heterogeneous fluvioglacial and alluvial multi-aquifer system that fines laterally northwards away from coarse clastic piedmont deposits into more stratified deep alluvial plain sediments. The coarse deposits forming the aquifers have high transmissivities and significant vertical permeabilities, and the urban boreholes abstract water from widely different depths.

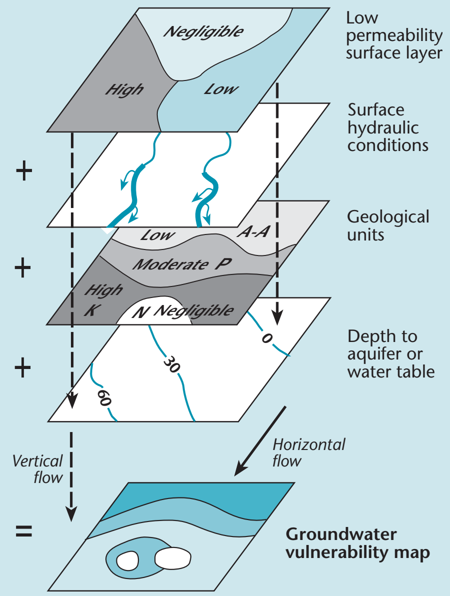
In both cities groundwater vulnerability assessments were conducted as part of the development of an aquifer protection policy and scarce resources necessitated the use of available data wherever possible. The vulnerability factors which were chosen depended not only on the local details of the hydrogeology but also on what information could be used either from studies conducted for other purposes or from very limited additional surveys. Each classification therefore varied (see table below) but relative hydraulic inaccessibility of the aquifer to surface contamination was used as the criterion in both cases.

*Components of aquifer vulnerability assessment in Bishkek and Narayanganj (from Morris et al., 2002).*

| Aquifer vulnerability components in rating system | Narayanganj | Bishkek |
|---|---|---|
| Presence and thickness of a low-permeability surface layer/upper aquitard | ✓ | ✓ |
| Geology of the aquifers | | ✓ |
| Depth to water table/thickness of unsaturated zone | ✓ | ✓ |
| Influent reaches of rivers/canals* | | ✓ |
| Presence of excavations into the upper aquitard** | ✓ | |

** Hydraulic feature important in upper unconfined aquifer in Bishkek.*
*** Hydraulic feature important in upper aquitard in Narayanganj.*

The vulnerability was mapped using a simple index and overlay system (see figure), which was combined with potentially polluting activity. A map of the groundwater resource was produced which could be used in stakeholder consultation exercises to help prioritise key issues and select the key elements of an urban aquifer protection policy in each city.




*Combining factors to make a vulnerability map.*

stage. Moreover, groundwater quality monitoring is often inadequate and poorly focussed. As a consequence, the impact on groundwater quality of various activities at the land surface are not reported. Thus agencies responsible for promoting activities that may potentially contaminate groundwater are often unaware of the impact of those activities. One consequence is that regulations to control waste disposal are absent or not enforced. Likewise, economic inducements are usually designed to increase output rather than to treat wastes or to limit the negative environmental impacts.

Groundwater is too often seen as a convenient, and relatively cheap, resource to be exploited rather than as a valuable but potentially fragile resource that needs to be sustained by protection and management

This lack of awareness of the potential threats to groundwater, by those planning development, often results in groundwater issues being absent from discussions in the planning stage. Unlike rivers or lakes whose contamination is generally highly visible and rapidly occurring, groundwater is out of sight and undergoes change over potentially long time scales, so that it can be years or decades before contaminants leached from the land surface will adversely affect a groundwater supply.

Figure 14 illustrates the vicious circle that can lead to groundwater quality degradation as lack of resources leads to lack of knowledge, preventing positive involvement in planning by regulatory agencies. In some situations corruption is also an issue frustrating effective measures. Clearly, in order to redress the balance, the importance of groundwater must be brought to the attention of those involved in planning development and infrastructure, who should be made aware of the fragility of this resource and the need to include its sustainable use as a tenet of the planning process.

*References*
*Bibliography (pp.120-125) numbers 9, 17, 18, 24, 26, 27, 36, 46, 48, 67, 75, 76, 77, 82 and 114 have been used in the production of this chapter.*

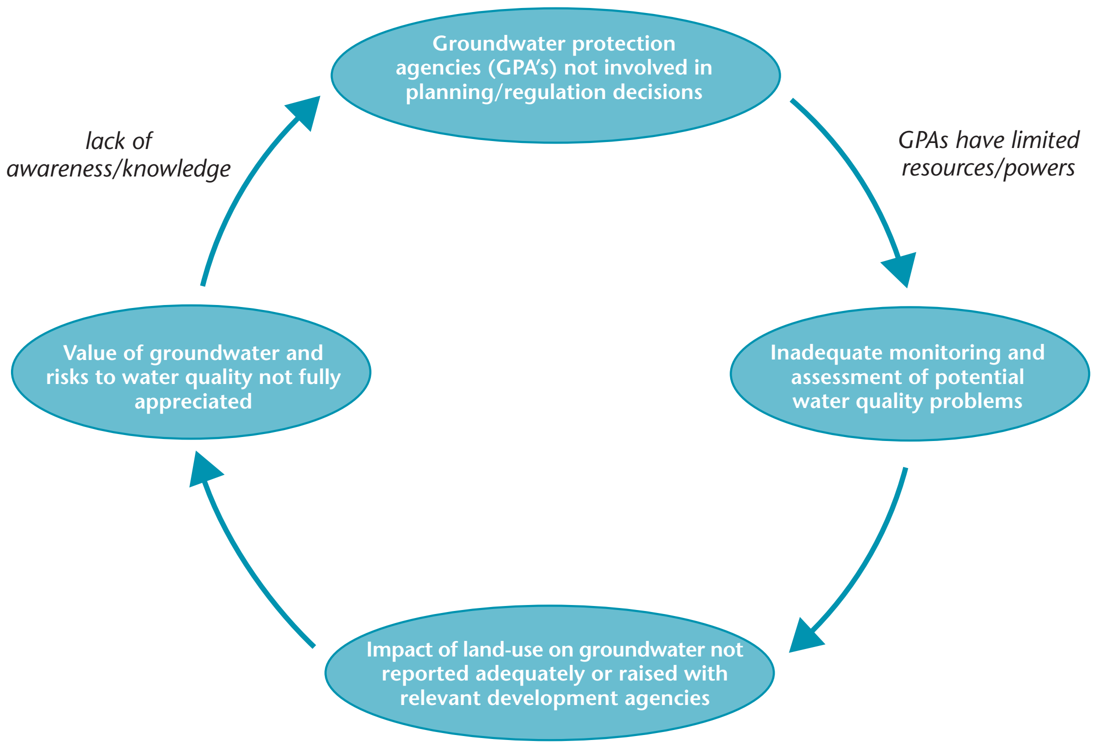



*Figure 14. The vicious circle: lack of resources ➔ lack of knowledge ➔ lack of planning.*

# URBANISATION PROCESSES AND EFFECTS OF OUR GROWING CITIES ON GROUNDWATER 5

## CONFLICTS IN USE OF THE URBAN SUBSURFACE

Cities may require water for public or private domestic water supply or industrial and commercial use. Whatever the mix of use and users, there is no doubt that urbanisation drastically affects local aquifer systems in terms both of quantity and quality. The most important factor to consider is whether the aquifer in question is located in a rural catchment relatively remote from urban activities, whether it is peri-urban and likely to be encroached upon in the near future or whether it actually underlies the city. In the first case, the resource will be affected by rural issues (see Chapter 7), but for the two latter cases and for cities that depend on water from both settings, read this chapter.

Cities overlying aquifer systems use the subsurface in a number of ways:

- as a source of water supply;
- for the disposal of waste water and as the receptor for solid waste;
- for urban engineering infrastructure (pipes, tunnels and foundations) and as a source of building material (stone, sand, aggregate).

The first two of these functions directly affect the underlying groundwater system. The benefits of such use are apparent from the outset, but the *costs* are long-term, and may not be appreciated at early, typically unplanned, stages of development (Table 14).

The perspectives of different users performing these vital urban infrastructure functions are dissimilar, and this in turn colours what they consider to be unacceptable groundwater degradation (Figure 15).

**Water supply** Groundwater is frequently a significant source both for the municipal water utility (typically operating relatively few high-yielding wells or well

**Table 14 Benefits and costs of using the urban subsurface**

| Function of subsurface | Initial benefits | Long-term costs |
|---|---|---|
| Water-supply source | Low capital cost<br>Staged development possible<br>Initial water quality better<br>Private and public supply can develop separately | Excessive abstraction can lead to:<br>- abandonment/reduced efficiency of wells<br>- saline intrusion risk in coastal cities<br>- subsidence risk in susceptible environments |
| On-site sanitation receptor | Low-cost community-built facilities possible<br>Permits rapid expansion under sanitary conditions<br>Uses natural attenuation capacity of subsoil | Sustainability of groundwater abstraction threatened if contaminant load exceeds aquifer assimilation capacity |
| Pluvial drainage receptor | Low capital costs<br>Conserves water resources<br>Less flood risk along downstream watercourses<br>Roof runoff provides dilution of urban contaminants | Contamination from industrial/commercial area and most highways |
| Industrial effluent/solid waste disposal stream management | Reduced manufacturing costs | Noxious effluent may prejudice groundwater quality<br>System favours irresponsible attitude to waste |

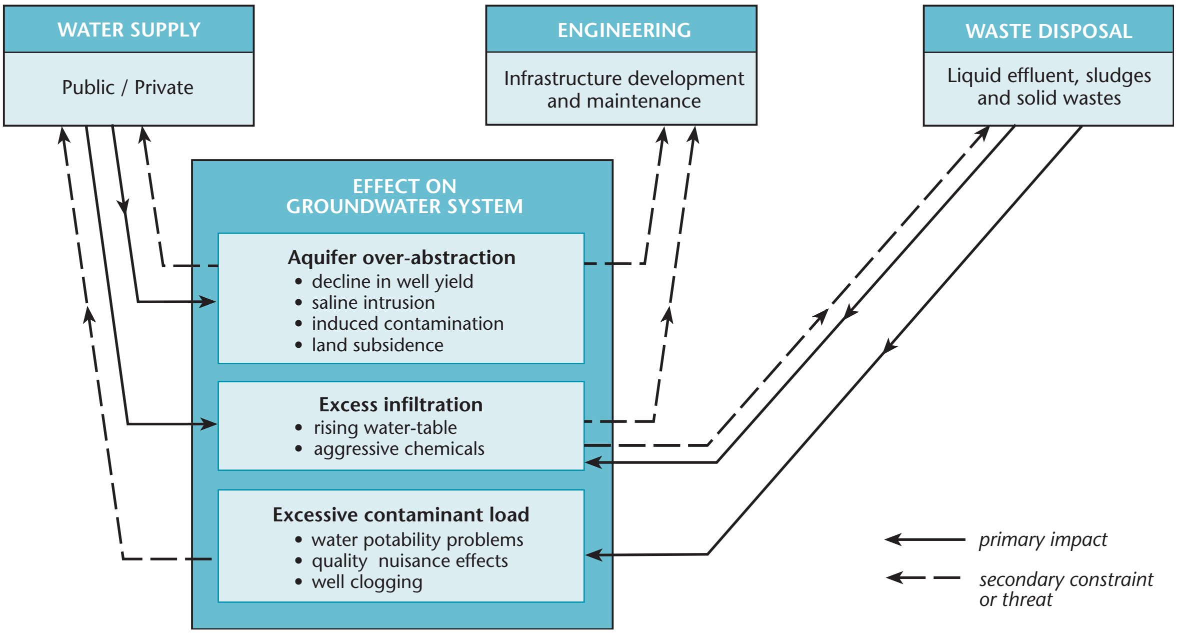



*Figure 15. Facets of degradation of groundwater system underlying a city, resulting from interaction between urban services.*

fields) and for the private sector (dispersed, ranging from individual domestic wells to large industrial supplies). In general terms they have similar interests. For both, groundwater degradation concerns are focussed on decreasing availability and deteriorating water quality, since these factors lead to rising water production costs, customer complaints about water quality nuisance factors, and/or to public health risks. Both sectors may also be anxious to establish or protect legal rights to abstract groundwater. However, their priorities on these problems and on the options for tackling them differ.

The municipal water-supply utilities can afford to take a broad view, and although affected by site-specific problems are most concerned about overall resource scarcity and about water quality problems that are costly or impossible to treat. They can consider developing alternative water supplies from beyond the city nucleus, into peri-urban areas and the rural hinterland. However, for many cities, public water supply price controls are as much a political as an economic issue, and this may constrain the required investment to bring in out-of-town supplies. Moreover, development of groundwater from beyond city limits may lead them into conflict with other major groundwater users, especially agricultural irrigators.

Private residential and industrial abstractors inevitably have to take a narrower view. They are primarily concerned about decreasing performance and deteriorating quality of the well(s) on the land they own or occupy. Their options for dealing with any problems that arise are limited, since they are generally restricted to the specific site concerned. They may be able to treat the groundwater supply (at least for some quality problems) or deepen their wells (in efforts to overcome problems of yield reduction due to falling water levels). Ultimately, the decision on continued use will depend upon the cost and reliability of the supply, compared with that available from the municipal water-supply utility.

**Waste water and solid waste disposal** A very different perspective comes from those concerned with waste-water elimination, even where this function is also the responsibility of the municipal water-supply company and even more so where it is organised separately.

The first issue that arises is whether it is physically possible to dispose of liquid effluents to the ground, which may not be the case where soil infiltration capacity is low, due to a shallow water-table or to relatively impermeable superficial strata. This may prevent the installation of on-site sanitation units, especially water-flush systems that need to dispose of large quantities of waste water through infiltration structures (for example septic tanks). A second set of issues is the impact of waste-water discharge and waste disposal on groundwater quality. In particular, whether:

- the type and density of on-site sanitation units is such as to seriously affect groundwater quality;
- the location and quality of downstream waste-water discharge from a mains sewerage system, together with its reuse for agricultural irrigation, is such as to prejudice the interests of groundwater users;
- the siting, design and operation of municipal/industrial solid waste disposal facilities is acceptable in terms of leachate impacts on groundwater quality.

For those planning and operating solid and liquid waste disposal facilities, their functions would be regarded as adversely affected if on-site sanitation systems became hydraulically dysfunctional (due either to excessive loadings or to the water table rising towards the ground surface) or if disposal activities unacceptably prejudiced downstream groundwater users. These issues rarely receive adequate consideration in the absence of a properly resourced and adequately empowered regulatory body.

**Engineering infrastructure** Municipal engineers responsible for developing and maintaining urban buildings and infrastructure need to consider changes in subsurface properties as a result of long term trends in groundwater levels. Issues include:

- falling water-table (due to heavy abstraction for water-supply)—physical damage to buildings and to underground services (such as tunnels and sewers) as a result of land settlement and subsidence;
- rising water-table (due to increased infiltration rates)—damage to subsurface engineering structures as a result of hydrostatic uplift or reduced bearing capacity, inundation of subsurface facilities, excessive ingress of groundwater to sewers, chemical attack on concrete foundations, subsurface facilities and underground structures.

For this group of users either a high or a low water table can be designed and engineered for, but stability (or at least predictability) of variations is a prerequisite; unanticipated changes/rates of change would constitute groundwater system degradation.

Faced with unexpected structural deterioration, those responsible for maintaining the urban buildings and infrastructure want to minimise such damage or try to recover remedial costs. This is rarely achieved, since unstable water levels may be due to several factors, so attribution to individual abstractors or polluters is difficult. Typically, and unsatisfactorily, the resultant costs have to be borne by the community at large, through urban taxes or rates, or even more unjustly by the owners of the damaged properties themselves.

**Managing urban groundwater degradation** Those planning and managing urban aquifers need to recognise not only that groundwater degradation can take various forms depending on the infrastructural function under consideration but also that they are strongly interrelated (Figure 15) and compromises will be necessary. In reconciling the demands of waste disposal and urban subsurface engineering as well as those of water supply, some degree of degradation will be unavoidable. Examining the effects each have on the subsurface can help develop the integrated approach so necessary to avoid serious long-term degradation and to encourage sustainable use of the aquifer system.

## PATTERN AND STAGE IN EVOLUTION OF A CITY UNDERLAIN BY A SHALLOW AQUIFER

All cities developing local groundwater resources differ in detail, but for many the typical stages of development can be summarised as shown in Figure 16.

In a growing city, as the demand for water and the need for safe disposal of waste water increase, so the changing combinations of supply source, from local to peri-urban to hinterland, are matched by new urban

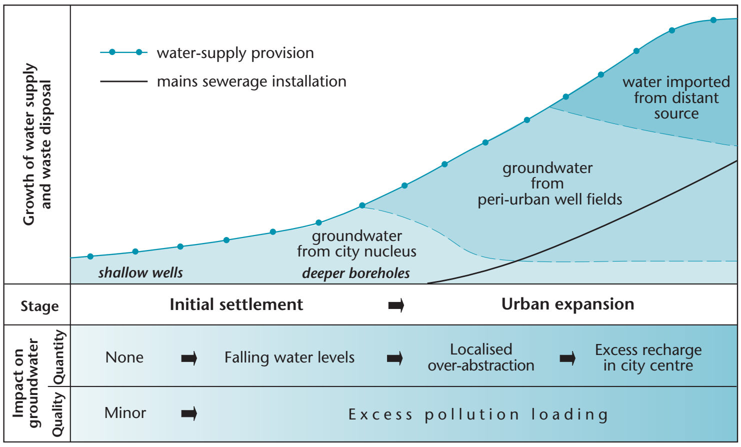



*Figure 16. Stages in the evolution of a water infrastructure in a city overlying a productive aquifer.*

sources of recharge such as losses from the piped infrastructure, on-site sanitation and pluvial drainage.

Subsurface water levels, both within the city and outside, undergo major changes as the twin pressures of competing demand for water and concern about the quality of the water shift the supply emphasis from city centre to peri-urban areas (Figure 17).

Although this pattern can be observed in many cities, the extent and rate of change will be highly variable, depending on the particular conditions of geology, the water supply and sanitary arrangements adopted. Nevertheless, as a general observation, the radical changes in frequency and rate of subsurface infiltration caused by urbanisation tend overall to increase the rate of groundwater recharge. If the underlying aquifer system is not utilised, or the shallow subsurface is not sufficiently permeable to allow the extra water to flow away, then groundwater levels will rise. Initially as the water table rises towards the land surface, tunnels and service ducts may suffer structural damage or be flooded, followed later by hydraulic and corrosion effects on building foundations and tunnel linings. In extreme cases, where the water table reaches the land surface, there may be a health hazard because septic tanks malfunction and water polluted with pathogens may accumulate in surface depressions.

On the other hand, where the city is underlain by a productive shallow aquifer and groundwater

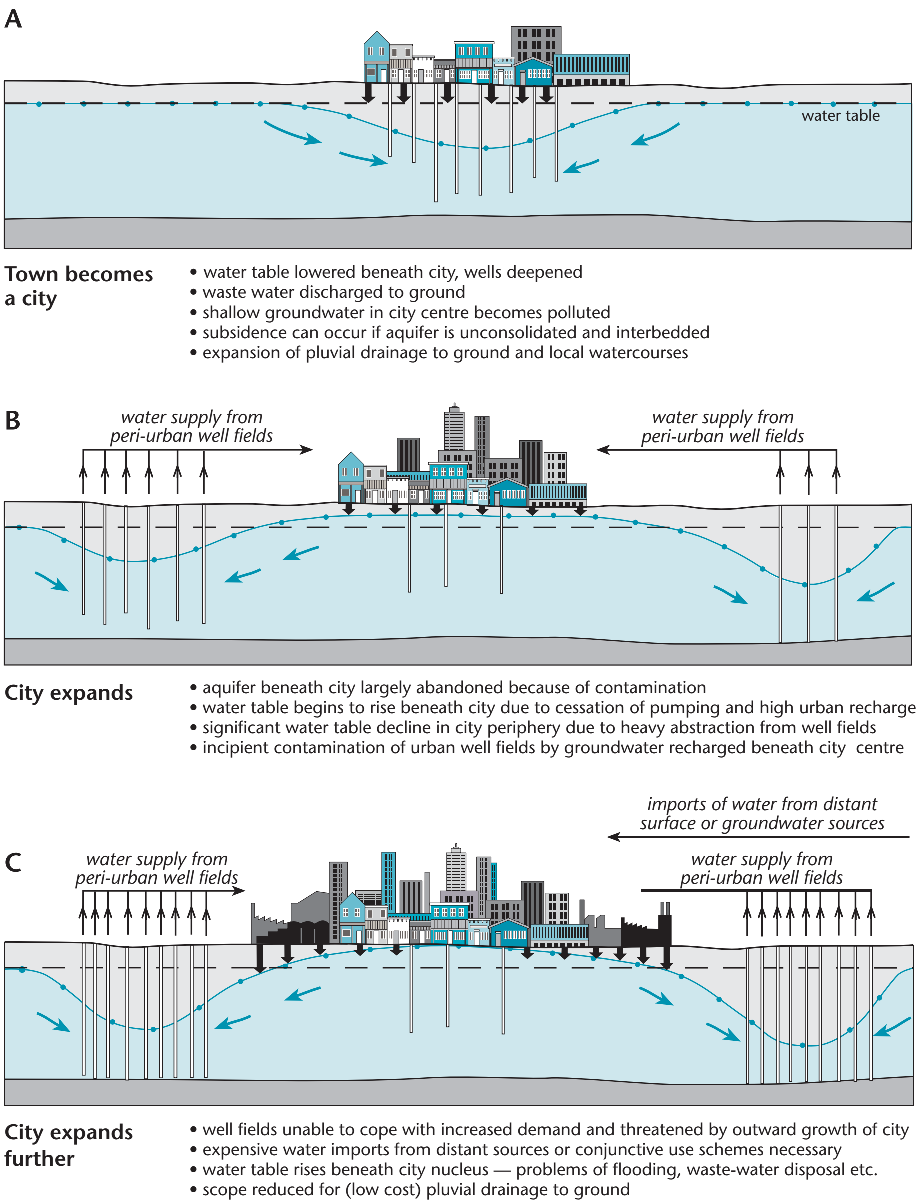



*Figure 17. Evolution of water supply/waste disposal in a typical city underlain by a shallow aquifer.*

abstraction is significant, a declining water table will mask the presence of increased urban infiltration rates and, indeed, in some unconsolidated aquifers the geotechnical problems associated with pumping-induced subsidence can result. However, as cities evolve, intra-urban abstraction often declines, either as a direct result of groundwater quality deterioration or as a consequence of unrelated economic factors. In these circumstances, the water table begins to recover and may eventually (over decades) rise to levels higher than it was before urbanisation as a result of the additional urban recharge. This can provide a widespread threat to a well-established urban infrastructure constructed when foundations, piped and cabled services did not need to be designed to cope with a water table near the surface. Thus the hydrogeological regime continues to exert a major control over an urban infrastructure, **even when the city has ceased to depend significantly on local groundwater for its water supply.**

## URBANISATION PROCESSES THAT AFFECT GROUNDWATER

Urbanisation affects both the quantity and quality of underlying groundwater systems by:

- radically changing patterns and rates of aquifer recharge;
- initiating new abstraction regimes, which may be cyclic in the long-term;
- adversely affecting the quality of groundwater.

### CHANGES IN RECHARGE PATTERNS

Recharge patterns can be affected by modifications to the natural infiltration system (for example, any change that makes the surface more impermeable), by change in natural drainage, and from the introduction of the water service network, which is invariably associated with large volumes of water mains leakage and waste-water seepage. The effects in terms of rates, area and duration are shown in Table 15. The extension of the water infrastructure may also be accompanied by the import of large volumes of water from outside the city.

The net effect for many cities is a rise in the total volume of recharge: the land-sealing effect of paving and building is more than compensated for by the enormous volume of water circulating through and lost from the ‘water infrastructure’ of pipes and from soakaways draining the built area (Figure 18). For example, in this way groundwater recharge in the city of Moscow has tripled.

Several city case-studies show that the effect is most

**Table 15 Impact of urban processes on infiltration to groundwater (from Foster et al., 1993)**

| Urbanisation process | Effect on infiltration: Rates | Area | Time base |
|---|---|---|---|
| *Modifications to the natural system* | | | |
| Surface impermeabilisation and drainage: | Reduction | Extensive | Permanent |
| Stormwater soakaways* | Increase | Extensive | Intermittent |
| Mains drainage* | Reduction | Extensive | Intermittent–continuous |
| Surface water canalisation * | Marginal reduction | Linear | Variable |
| Irrigation of amenity areas* | Increase | Restricted | Seasonal |
| *Introduction of water-service network* | | | |
| Local groundwater abstraction | Minimal | Extensive | Continuous |
| Imported mains water-supply leakage | Increase | Extensive | Continuous |
| On-site (unsewered) sanitation ** | Major increase | Extensive | Continuous |
| Piped sewerage: leakage in urban areas* | Some increase | Extensive | Continuous |
| Piped sewerage: downstream disposal** | Major increase | Riparian areas | Continuous |

*Also has (**) major and (*) minor impact on groundwater quality*

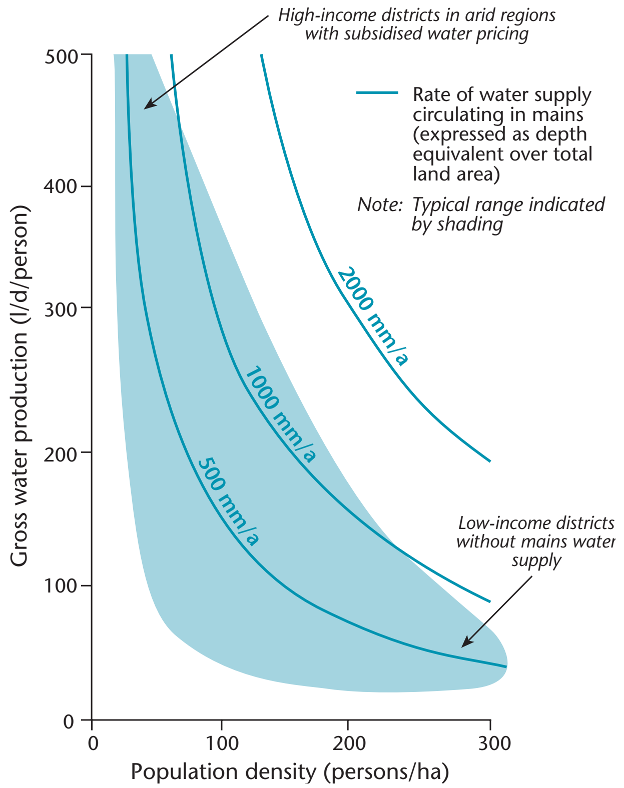



*Figure 18. Rates of circulation in water supply mains in urban areas expressed as equivalent recharge.*

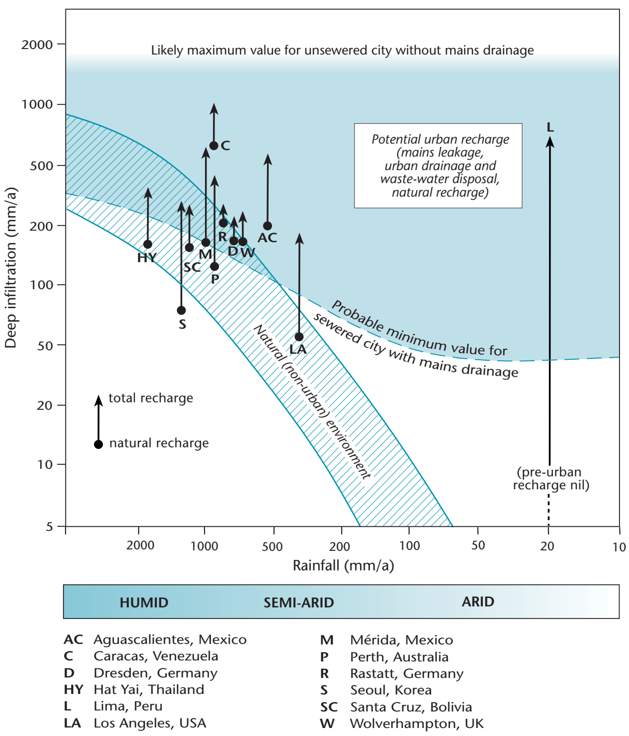



*Figure 19. Increase in groundwater recharge due to urbanisation (modified from Foster et al., 1993; Krothe et al., 2002; Eiswirth et al., 2002).*

pronounced in cities where on-site sanitation or amenity watering is important, and in arid and semi-arid climates where the new sources may increase the total infiltration several times over the pre-urban situation (Figure 19). Environmental degradation and health problems can then occur if local geological or topographical conditions impede drainage and result in groundwater flooding (Box 19).

## NEW GROUNDWATER ABSTRACTION REGIMES AND THEIR CONSEQUENCES

Groundwater abstraction necessarily results in a decline in aquifer water level. Where such abstraction is limited, groundwater levels stabilise at a new equilibrium such that flow to the area balances groundwater pumping. However, where groundwater withdrawal is heavy and concentrated, such that it greatly exceeds average rates of local recharge, water levels may continue to decline over decades. Serious declines reduce well yields, which can provoke an expensive and inefficient cycle of borehole deepening to regain productivity, or even premature loss of investment due to forced abandonment of wells.
In some unconsolidated aquifers, groundwater quality also may suffer as an indirect result of pumping-induced subsidence. Differential subsidence causes damage not only to individual buildings and roads, but also to piped services routed underground, by increasing water mains leakage and rupturing sewerage systems, oil pipelines and subsurface tanks. This can cause serious contamination of underlying aquifers.

Major changes in hydraulic head distribution within aquifers can lead to the reversal of groundwater flow directions, which can in turn induce serious water-quality deterioration as a result of ingress of sea water beneath coastal cities, up-coning or intrusion of other saline groundwater, as in the case of Bangkok, Jakarta, Madras, Manila and Barcelona, and induced downward leakage of polluted water from the surface elsewhere. Thus severe depletion of groundwater resources is often compounded by major water-quality degradation.

Some cities that have previously pumped extensively from an underlying aquifer system experience groundwater level rebound if the pumping regime moderates. This has already been observed in Europe and the USA (for example Barcelona, Berlin, Birmingham, Budapest, Houston, Liverpool, London, Milan, Moscow) and typically has been observed in industrial cities where earlier periods of expansion resulted in heavy pumping for manufacturing or for

## BOX 19 PATTERNS OF URBAN GROUNDWATER: RISING WATER LEVELS

The water balance of an aquifer once its catchment is urbanised becomes much more complex due to the presence of both new potential sources of recharge and of new abstraction. This effects water levels, which rise and fall to maintain a balance between inflow and outflow. In many aquifer systems, these changes will not be immediately obvious due to the large volume of available storage, and it may be many years before they reach equilibrium with the hydrological changes induced by urbanisation. Disregard of the lag in response time between cause and effect in aquifer systems can unwittingly compound aquifer degradation effects, which can arise from changes in inflow and outflow components. An example of the problem is one of the paradoxes of arid-zone hydrology, and is seen in the waterlogging problems experienced by several Arabian cities due to increased urban recharge.

The city of **Riyadh**, Saudi Arabia grew from a town of 20 000 in 1920 to more than 1.2 million in the 1990s. Per capita consumption rates also rose, to more than 600 l/person/day in 1990. By the early 1980s, the high water demand was met by long-distance imports of desalinated water. This coincided with reduced pumping from a deep underlying limestone aquifer, abandoned due to serious pollution. New urban recharge sources have arisen from high water mains leakage rates (over 30 per cent), underground storage tank losses, percolation from septic tank systems and over-irrigation of amenities such as parks, road verges, gardens.

Waterlogging has occurred because much of the city is underlain by a shallow aquitard and adequate drainage through it cannot occur. The vertical permeability is low and there is now insufficient pumping by users from the deep aquifer system to provide a vertical hydraulic gradient to induce leakage from the overlying aquitard. The waterlogging has caused deformation of basements and pipe networks, and dewatering equipment was required to alleviate flooding. Horizontal drains have been demonstrated to be ineffective, and the problem has required more complex and expensive pumping of the aquifer underlying the aquitard to induce drainage. (Rushton and Al-Othman, 1993).

Thus for Riyadh an urban water management strategy to control the waterlogging problem would need to include not only control of mains and tank leakage, and over-irrigation (inputs), but also a means of coping with the large volume of imported water, for example local groundwater pumped from the deep aquifer system could be substituted for non-sensitive uses such as amenity irrigation.

Another Arabian example shows that rises in level do not have to be more than a very few metres before degradation effects become serious. Both Kuwait and Doha share with Riyadh the pattern of much increased recharge due to a rapid growth in population, an increase in per capita water consumption and water imports from desalination plants, high water mains leakage, amenity over-irrigation and on-site sanitation returns. But in addition both are low-lying coastal areas with underlying evaporite deposits, and evaporative salinisation of the near-surface adds serious water quality deterioration to the geotechnical effects described for Riyadh. The percolating desalinised water dissolves salts and makes shallow groundwater much less attractive for other, non-potable uses as well as making it more aggressive and harmful to concrete and steel reinforcing materials.

A typical groundwater budget from one of these arid-zone cities shows how insignificant the contribution of recharge from rainfall is in comparison with human sources. The corollary is that urban planning and control policies, if effective and enforced, can be very influential in controlling the extent and rate of groundwater degradation. For instance, hydrographs from monitoring wells confirm the groundwater budget calculation that garden irrigation is a very important new recharge source. Control of such domestic and municipal over- irrigation could be put in place very quickly and comprise either financial (metering and increasing block tariffs, drip irrigation incentives) regulatory (sprinkler/hosepipe bans) or operational (supply restrictions, pipe resizing) measures.

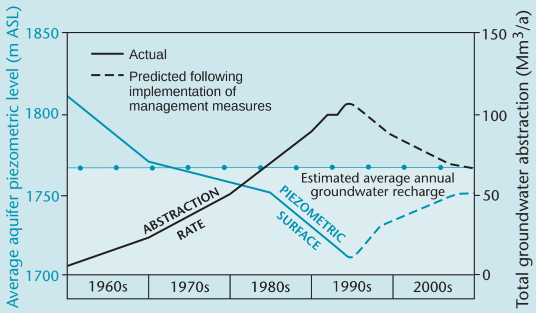
**Groundwater budget for a typical Arabian Gulf coastal city (from Walton, 1997)**

| Groundwater recharge source | % total | Groundwater outflow source | % total |
|---|---|---|---|
| Seepage from amenity over-irrigation | 45 | Seepage and channelling to coast | 46 |
| Mains supply leakage | 30 | Groundwater abstraction | 21 |
| Septic tank/soakaway seepage | 22 | Drainage into sewerage system and stormwater drains | 25 |
| Effective recharge from rainfall | 3 | Groundwater flow inland | 6 |
| - | - | Groundwater evaporation | 2 |
| *Total recharge inflows=29.8 x $10^6$ $m^3$/a* | 100% | *Total discharge outflows=28.9 x $10^6$ $m^3$/a* | 100% |

*Addition to storage= 0.9 x $10^6$ M $m^3$/a, resulting in typical annual water table rise of 0.3-0.4m*

## BOX 20 PATTERNS OF URBAN GROUNDWATER: FALLING WATER LEVELS

Many cities worldwide experience the effects of falling water levels. The city of Querétaro is typical of many in Mexico trying to manage demand and supply in an arid climate. The city (population 700 000) draws most of its water supply from 55 production boreholes supplying 175 Ml/d. However, over-exploitation of the Valle de Querétaro aquifer for both urban water supply and agricultural irrigation has depressed the potentiometric surface by more than 100 m, requiring borehole depths of up to 350 m and pumping lifts of 130 to 160 m. The steadily falling water levels (3.5 m/a) have increased energy costs for water production and forced a regular up-rating of borehole pumps and reorganisation of the distribution system.




*Change in groundwater abstraction and aquifer water level, Querétaro valley, Mexico*

Over-exploitation of the aquifer has also resulted in compaction of the valley-fill sequence which is alluvial, volcanic and lacustrine in origin and shows 0.4 to 0.8 m of differential subsidence along faults. Serious building and infrastructure damage has resulted (for example ruptured water-mains and municipal/industrial sewers), while opening of vertical fissures at the ground surface has increased groundwater pollution vulnerability.

The municipal water-supply undertaking (CEAQ) uses about 70 per cent of the groundwater abstracted from the Valle de Querétaro aquifer and in the mid-1990s implemented a 10 year aquifer stabilisation plan. Measures are comprehensive and include reduction of mains leakage, improved operational efficiency, demand management and the innovatory approach of financing irrigation technology improvements, water use efficiency, and changes in cropping practice in the agricultural sector in return for voluntary surrender of water rights. By providing secondary treated waste water in exchange for peri-urban irrigation well water-rights, CEAQ have planned to limit importation of scarce groundwater from aquifers in neighbouring valleys up to 50 km away to less than 45 Ml/d.

public supply (Box 21). Particular problems occur where aquifer water levels have been depressed over many years, during which time foundations, tunnels and other subsurface structures are constructed in the unsaturated upper aquifer. Subsequently, for various reasons, abstraction rates decline and water levels start to recover, sometimes at a rate accelerated by new sources of urban recharge such as water mains and sewer leakage. Such leakage can occur for instance as the pipe infrastructure ages and renewal rates fail to keep pace, or from natural events such as seismic tremors. Problems arise as water levels recover to depths that would start to affect deep urban infrastructure (metro tunnels, high-rise building foundations), presenting problems not only of stability (subsidence hazard) and flooding but also of corrosion if the water is chemically aggressive.

An additional problem of salinity may affect those cities located on the coast or on tidal estuaries because saline intrusion of the aquifer induced under former heavy pumping conditions may have caused sufficient deterioration in water quality to pose a corrosion hazard to reinforcing materials in subsurface structures (for example Liverpool) or an ecological hazard to surface water habitats in urban parks or river amenity areas once the water table approaches ground level.

It is important to understand the relative contribution made by each component of the groundwater budget in order to design the mitigation measures. For instance, in Moscow water mains and sewer leakage are important contributors to groundwater rebound, whereas in Barcelona, recovery was much controlled by the very steep reduction in industrial abstraction between the 1960s and the mid 1990s as industry moved out of the city. Although losses remained sufficiently large to contribute to the problem, during the same period, mains supply leakage was reduced by over 40 per cent and piped sewerage systems replaced.

A variation in the pattern can arise in cities with a history of underground coal mining, where water levels can rebound once extraction declines or ceases and tunnel dewatering ceases (for example Glasgow and Wigan, UK). The act of mining usually renders the coal-bearing formations much more permeable (see Chapter 6), while the effects of subsidence and other displacements can provoke lateral or vertical migration of rising saline or acidic mine drainage into adjacent or overlying aquifers still used for potable water supply.

## BOX 21 PATTERNS OF URBAN GROUNDWATER: GROUNDWATER REBOUND

The groundwater level rebound problem is well illustrated in several English cities. The rate and magnitude of rise is most striking in central London, where between 1967 and 2001 water levels had risen steadily by over 50 m at a rate of about 1.5 m/year (see Figure A). This rise threatens the underground railway system, constructed at various dates since the 1890s, particularly the deeper lines, and the stability of building foundations. As water levels rise through overlying pyrite-bearing sands and silts above the top of the limestone aquifer (the Chalk) there are also water quality concerns from increasingly aggressive pH-reduced water.

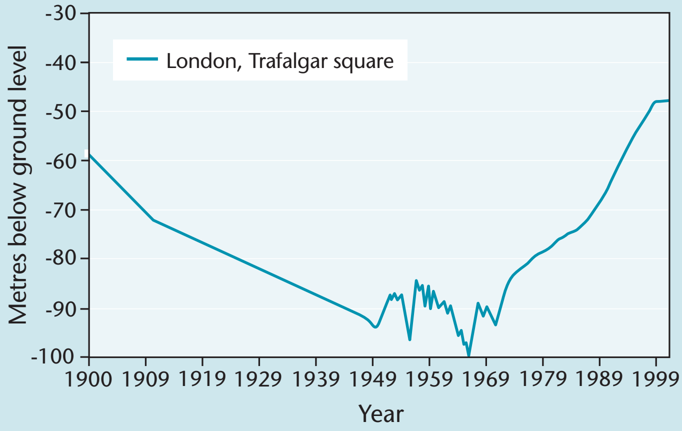



*Figure A. Rising water level in the Chalk limestone aquifer below central London, UK.*

Rising groundwater in the Triassic sandstone aquifer underlying the port of Liverpool demonstrates the effect rebound can have on coastal cities (Figure B). There, deterioration in groundwater quality due to saline intrusion and diffuse urban pollution together with diminished water use by heavy industry have greatly reduced pumping since the 1970s. Rebound has affected most notably transport tunnels, including the Liverpool Loop railway tunnel, which was constructed in the early 1970s to enable trains from the Mersey Tunnel to turn around beneath the city centre via several stations before re-entering the tunnel. The circular section, single track, permeable tunnel was excavated in the unsaturated zone at a time when water levels were below the tunnel and groundwater ingress was minimal.

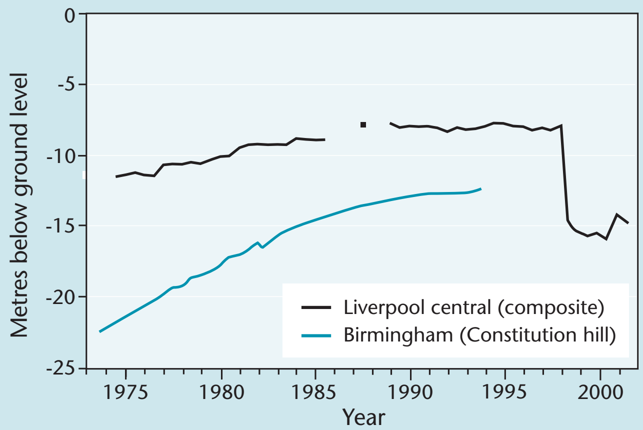



*Figure B. Rising water levels in the Permo-Triassic sandstone aquifer below Birmingham and Liverpool, UK.*

Unfortunately the rising water table in central Liverpool not only progressively increased dewatering requirements but also the brackish water caused track corrosion and interfered with the automatic failsafe signalling systems in the tunnel, stopping trains even when the track was clear. The length, location and depth of the tunnel serves to intercept groundwater and protect many other shallower structures at risk. The composite hydrograph from two monitoring wells charts the growth of this problem (which necessitated major remedial engineering works) and shows the impact of remedial extra dewatering of the tunnel in 1998.

In Birmingham, the rise is about 10m between 1974 and 1994 and only localised dewatering boreholes in the unconfined sandstone aquifer have averted flooding of factory basements and tunnels.

In the cases of both Birmingham and Liverpool, the high available storage of the aquifer (storage coefficient typically about 15 per cent) has kept rebound rates modest, but it disguises the fact that very large volumes of water are involved, such that dewatering operations need to be both timely and large scale.

## EFFECTS ON GROUNDWATER QUALITY

The net effect on the quality of recharge is generally adverse, especially if waste water is an important component (Box 22). Urbanisation processes are the cause of extensive but essentially diffuse, pollution of groundwater by nitrogen and sulphur compounds and rising levels of salinity. These compounds may not be of serious health significance in themselves, but can serve as indicators of more widespread groundwater contamination by industrial chemicals, petroleum products, solvents and other synthetic compounds that are not readily degradable. In resource surveillance programmes most of these compounds may not be analysed for on a regular basis due to constraints of cost and capacity (Table 16). On a more localised basis, pollution by pathogenic bacteria, protozoa and viruses is also encountered (Box 23), but the ability of many aquifers to eliminate, or at least attenuate, these contaminants should not be underestimated (Box 24). The maintenance of sanitary well and borehole construction standards and proper well abandonment practices can contribute greatly to the containment of microbial contamination in all but the most vulnerable aquifers.

**Table 16 Impact on groundwater quality from various sources of urban aquifer recharge (from UNEP, 1996)**

| Recharge source | Importance | Water quality | Pollutants/Pollution indicators |
|---|---|---|---|
| Leaking water mains | Major | Excellent | Generally no obvious indicators |
| On-site sanitation systems | Major | Poor | N, B, Cl, FC, DOC |
| On-site disposal/leakage of industrial waste water | Minor-to-major | Poor | HC, diverse industrial chemicals, N, B, Cl, FC, DOC |
| Leaking sewers | Minor | Poor | N, B, Cl, FC, $SO_4$, diverse industrial chemicals |
| Pluvial drainage from surface by soakaway drainage | Minor-to-major | Good-to-poor | N, Cl, FC, HC, DOC, diverse industrial chemicals |
| Seepage from canals and rivers | Minor-to-major | Moderate-to-poor | N, B, Cl, FC, $SO_4$, DOC, diverse industrial chemicals |

*B* *boron*
*Cl* *chloride and salinity generally*
*DOC* *dissolved organic carbon (organic load)*
*FC* *faecal coliforms*
*HC* *hydrocarbons (fuels, oils and greases)*
*N* *Nitrogen compounds (nitrate or ammonium)*
*$SO_4$* *sulphate*

The occurrence of more serious contaminants in aquifers tapped at depth for urban supply will depend on the:

- characteristics of the contaminants (physical properties, mode of disposition to the urban subsurface, intensity and duration of the load (see Chapter 4);
- attenuation capacity of the intervening strata (Table 17);
- way the aquifer system responds geochemically to the imposed contaminant loads in urban recharge (Boxes 25A, B, Boxes 16 and 17 in Chapter 4 and the on-site sanitation material in Chapter 7).

Similarly, the impact of such contaminants on the supplies will depend on both the end-use and the relative acceptability in terms of toxicity and purity as represented by water standards.

## IMPLICATIONS OF URBAN PROCESSES FOR CITY WATER RESOURCES

Pollution of urban aquifers is a widely recognised phenomenon. The typical response is the abandonment of at least the shallow zone for public water supply, with water utilities either opting for deeper wells or relocation to peri-urban or rural areas as an operational alternative to extensive treatment. While these are perfectly valid operational responses, the long-term implications need to be taken into consideration.

**Table 17 Transport characteristics of the common urban contaminants/contamination indicators**

| CONTAMINANT | SOURCE | ATTENUATION MECHANISM | | | | PERMITTED DRINKING WATER CONCENTRATION | MOBILITY | PERSISTENCE |
|---|---|---|---|---|---|---|---|---|
| | | Biochemical Degradation | Sorption | Filtration | Precipitation | | | |
| Nitrogen (N) | Sewage | ✓ | ✓* | ✖ | ✖ | Moderate (10–20 mg N/l) | Very high | Very high |
| Chloride (Cl) | Sewage, industry, road de-icer | ✖ | - | ✖ | ✖ | High | Very high | Very high |
| Faecal pathogens (FCs) | Sewage | ✓✓✓ | ✓✓ | ✓✓✓ | ✖ | Very low (<1 per 100 ml) | Low-moderate | Generally low |
| Dissolved organic carbon (DOC) | Sewage, industry (esp. food processing textiles | ✓✓✓ | ✓✓✓ | ✓ | ✖ | Not controlled | Low-moderate | Low-moderate |
| Sulphate ($SO_4$) | Road-runoff, industry | ✓† | ✓ | ✖ | ✓ | High | High | High |
| Heavy metals | Industry | ✖ | ✓✓✓ | ✓‡ | ✓✓ | Low (Variable) | Generally low unless pH low (except Cr [VI]) | High |
| Halogenated solvents (DNAPLs) | Industry | ✓ | ✓ | ✖ | ✖ | Low (10–30 µg/l) | High | High |
| Fuels, lubricants, oils, other hydrocarbons (LNAPLs) | Fuel station spillages, industry | ✓✓✓ | ✓✓ | ✖ | ✖ | Low (10–700 µg/l BTEX§) | Moderate | Low |
| Other synthetic organic | Industry, sewage | Variable | Variable | ✖ | ✖ | Low (Variable) | Variable | Variable |

KEY
✓✓✓ highly attenuated ✓✓ significant attenuation ✓ some attenuation ✖ no attenuation
* Ammonia is sorbed † Can be reduced ‡ where occur as organic complexes § Aromatic compounds with health guideline limits

## BOX 22 COMPOSITION OF URBAN WASTE WATERS

Urban waste water is comprised mainly of water (99.9 per cent) together with relatively small concentrations of suspended and dissolved organic and inorganic solids. Among the organic substances present in sewage and its microbiological load are carbohydrate, lignin, fat, soap, synthetic detergent, protein and its decomposition products, as well as various natural and synthetic organic chemicals from process industries. Concentrations of these synthetic compounds tend to be much higher in developed countries compared with developing countries, reflecting the nature and degree of industrialisation. The table below shows the concentrations of the major inorganic constituents of urban waste water in both humid and semi-arid climates. In many arid and semi-arid countries, such as Jordan and Mexico, water use can be relatively low and sewage therefore tends to be more concentrated. In wetter countries such as Thailand and Bolivia, sewage tends to be more dilute.

**Inorganic components of urban waste water from developing cities**

| | | *Concentration (mg/l except SEC)* | | | |
|---|---|---|---|---|---|
| | **WHO-dwgl*** | **Humid** | | **Semi-arid** | |
| | | **Hat Yai,** | **Sta Cruz,** | **León,** | **Amman,** |
| Electrical Conductivity (SEC) _S/cm | - | 345 | 890 | 2500 | 2350 |
| Dissolved organic carbon | - | 10 | 35 | 96 | 40 |
| Sodium | 200 | 35 | 73 | 111 | 235 |
| Potassium | - | 13.5 | 19.3 | 16.2 | 37 |
| Bicarbonate | - | 130 | 440 | 685 | 830 |
| Sulphate | 250 | 12 | 40 | 81 | 35 |
| Phosphate | - | 1.5 | 6.1 | 4 | 19 |
| Chloride | 250 | 45 | 57 | 310 | 530 |
| Nitrogen | 11.3** | | | | |
| | 0.9*** | 11 | 39 | 40 | 93 |
| Boron | 0.5 | 0.05 | 0.08 | 0.26 | 0.56 |

* *Drinking water guideline value, WHO, 1998* ** *as nitrate* $NO_3^-$ *** *as nitrite* $NO_2^-$

In multiaquifer systems, extensive pumping from deeper strata will depress the potentiometric surface, and the resultant head differences between shallow and deep aquifer water levels may induce downward leakage of water, which is usually polluted, into the lower aquifer if the intervening beds are sufficiently permeable. The long time scale that is typically involved in leakage to the deep aquifer means that only the most persistent pollutants will reach supply intakes, which will also benefit from the effects of dilution by pristine deep groundwater (Boxes 25A; B). In such circumstances, maintenance of high-quality deep groundwater can depend on effective prioritisation of the deeper aquifer use. For instance, high-quality water would be squandered if used for non-sensitive industrial supply, cooling or amenity irrigation where these demands could be met from continued use of the shallow aquifer. Matching quality to end use has the triple advantage of intercepting and recycling water of poor quality to a less sensitive function, reducing aquifer leakage and conserving scarce high-quality deep groundwater for the highest value use (typically potable supply).

Another problem that is likely to occur if depressed water levels rebound after a long period of intensive pumping is that pollutants, such as LNAPLs, that have entered the aquifer in the past can be lifted and carried to springs or wells. An example of this is New York, where oil spilled in the 1950s was mobilised by a rising water table, rebounding as a consequence of reduced pumping. The oil rose with it, until in 1978 it began to enter a tributary of the East River.

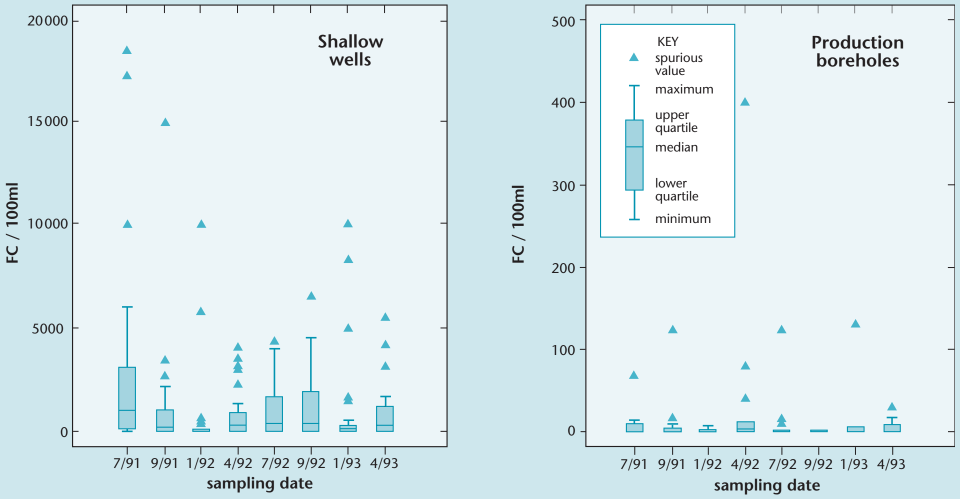
Total or near-abandonment of an urban aquifer in favour of supplies from the hinterland will put large volumes of imported water into the water and waste-water systems. The detailed response will depend on the individual city, its geology and circumstances. Negative effects may include waterlogging of lowland areas if the near-surface strata are poorly permeable or the water table is already high. Positive results include the regeneration of urban watercourses and springs long dewatered by historic pumping.

For some urban areas, abandoning a shallow aquifer due to progressive contamination is not an option in

**BOX 23 GROUNDWATER CONTAMINATION BY PATHOGENS: A CASE STUDY FROM MÉRIDA, MEXICO**

The city of Mérida lies on the karstic limestone Yucatán peninsula of Mexico. It has no mains sewerage, and most of the waste water is disposed directly to the ground via septic tanks, soakaways and cesspits which are completed in the karstic limestone and are commonly sited only 1 to 3 m above the water table. The limestone is highly permeable and provides the entire water supply for the city. Most of the water comes from well fields located on the city periphery, but in the early 1990s around 30 per cent was extracted from boreholes within the urban area.

The fissured nature of the limestone and shallow depth to the water table mean that water movement to the aquifer is frequently rapid. The unsaturated zone provides virtually no attenuation capacity, as the aperture of the fissures is many times larger than the pathogenic micro-organisms. Not surprisingly, gross bacteriological contamination of the shallow aquifer occurs, with faecal coliforms (FCs) typically in the range 1000 to 4000/100 ml; permitted concentrations in drinking water of  is less than 1/100 ml.




*Faecal coliforms in groundwater, Mérida.*

The faecal coliform counts fluctuate seasonally; lowest values are observed in the drier season (January to April) and the highest in the wet season (June to September). This variation suggests that there is less attenuation during the rainy season, presumably because the increased hydraulic surcharge (due to urban stormwater entering the aquifer) causes the fissures to transmit water, including polluted surface run off. The contamination is much more pronounced in shallow dug wells than in deeper boreholes that typically tap depths of 18 to 38 m but are also significantly affected. The presence of faecal coliform indicator bacteria at depth may be due to vertical fractures, or to the malfunction of a small number of deep waste-water disposal systems which inject into the underlying saline aquifer.

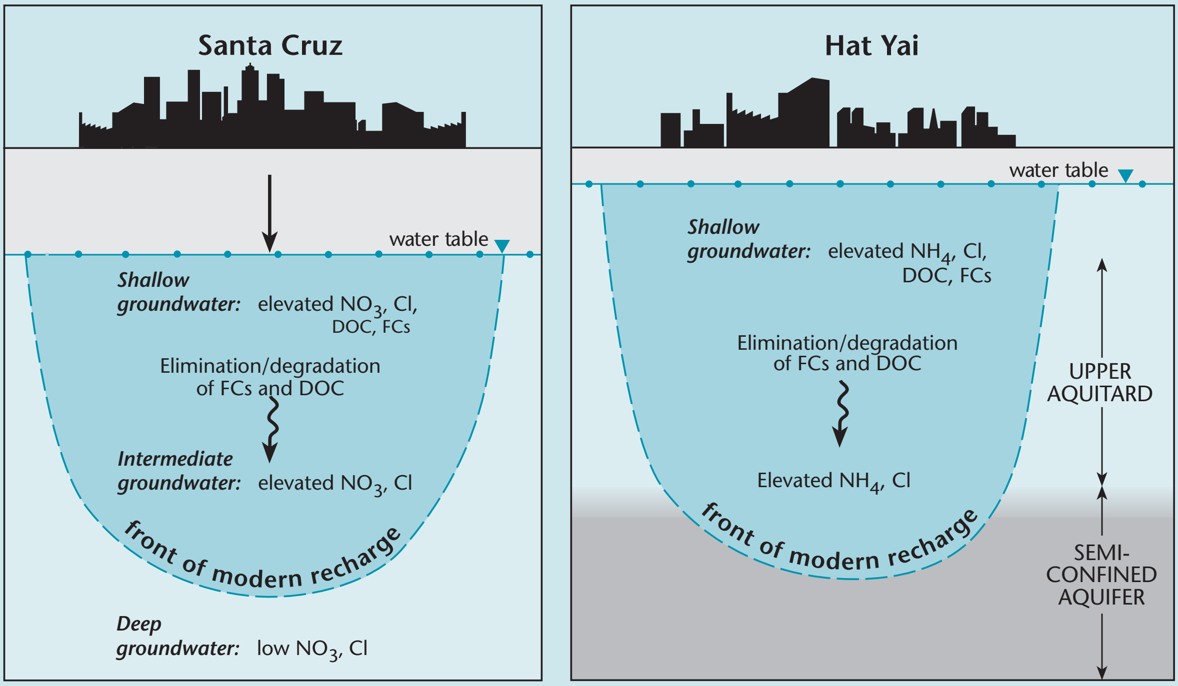
social or economic terms. For example, many cities in the developing world have a reticulated supply for middle- and high-income areas, but low income and socially deprived districts are partially or completely dependent on the underlying shallow aquifer for handpumps and public standpipe community water supplies and for on-site sanitation. In such situations where the users may not have an alternative supply, their planning authority or public health representatives will need to consider how to manage the twin demands of supply and waste disposal in such a way that both functions can continue without incurring unacceptable community health risks. (See also the section on on-site sanitation in Chapter 7 for more detail on groundwater contamination risk.) There is no easy prescriptive solution to such conflicting demands: different aquifer settings vary in their pollution vulnerability and will require different solutions (Box 26). One measure, for instance, would be to use urban housing density controls to limit contaminant loading and to enforce spatial separation criteria between supplies and latrine units.

*References*
*Bibliography (pp.120-125) numbers 9, 16, 43, 45, 49, 51, 57, 73, 76, 81, 83, 99, 100, 108, 112, 113 and 116 have been used in the production of this chapter.*

**BOX 24 CONTAMINANT ATTENUATION AT WORK: EFFECTS ON URBAN AQUIFERS IN THAILAND AND BOLIVIA.**

The effects of attenuation on some contaminant classes can be seen in the processes of waste-water infiltration below the cities of Hat Yai in Thailand and Santa Cruz in Bolivia. Large areas of both are unsewered*, so that significant quantities of domestic and some industrial wastes are discharged to the subsurface. Principal contaminants entering the subsurface in this way include nitrogen, chloride, long-chain organic compounds and microbiological waste including faecal pathogens. Shallow groundwater beneath both cities is contaminated, and indicators show elevated concentrations of nitrogen (as ammonium beneath Hat Yai where the water table is shallow and as nitrate beneath Santa Cruz, where it is deeper), chloride, faecal coliforms and dissolved organic carbon (DOC). See figure.

Both cities are dependent on groundwater obtained from deep semiconfined aquifers, but pumping has induced downward leakage. Although nitrogen and chloride indicators show penetration of the front of modern recharge, faecal coliforms (FC) and elevated levels of DOC were generally not recorded in the deeper groundwaters, where water quality is excellent. The processes of attenuation and elimination are thus well illustrated in both cities, which have distinctive hydrogeological settings.




*Impact on water quality from penetration of urban recharge in Santa Cruz and Hat Yai.*

* *Since the case-study in Santa Cruz in the mid-1990s, piped sewerage has been significantly extended*

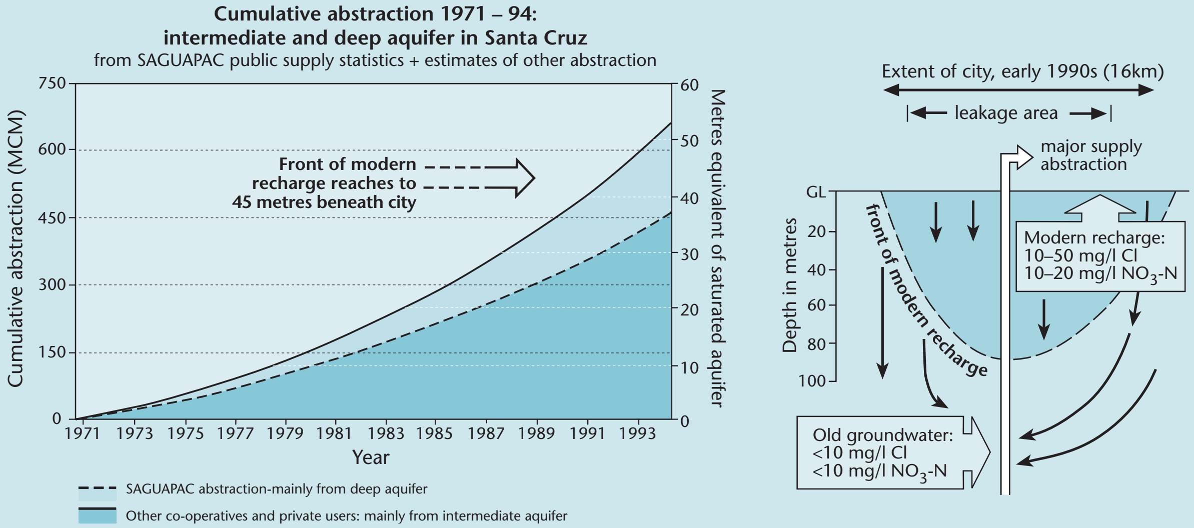
## BOX 25A THE ENGINE DRIVING WATER QUALITY CHANGE: DEEP PENETRATION OF URBAN RECHARGE IN SANTA CRUZ

Santa Cruz de la Sierra, Bolivia, is a low-rise, relatively low-density fast-growing city located on the plains to the east of the Andes. Its municipal water supply is derived entirely from well fields within the city limits, extracting from deep semi- to unconfined alluvial aquifers. Mains water is provided by cooperatives of which the largest is SAGUAPAC. The supply in 1994 was 98 Ml/d from about 50 boreholes (90 to 350 m deep). There are also many private wells (some 550 in 1991) used to supply small business and some homes. These wells are generally less than 90 m deep and draw water principally from the shallow aquifer.

The city has relatively good coverage of piped water supply, but until the 1990s only the older central area had mains sewerage; most domestic and industrial effluent and pluvial drainage were disposed to the ground. The main additions to groundwater recharge over the natural infiltration of excess rainfall were the on-site disposal of waste water and leakage from the mains water supply. Seepage from the nearby Rio Piray is also believed to be significant, but is difficult to quantify precisely. There is no pattern of falling water levels; this is due to the abundance of recharge and the ease with which water can enter the subsurface and percolate to the shallow aquifer.

Groundwater in the deeper aquifer, below 100 m, is of excellent quality, similar to the shallow aquifer upgradient of the city, and this represents the natural condition. However, the uppermost aquifer, above 45 m, shows substantial deterioration, with elevated nitrate and chloride beneath the more densely populated districts. These are derived from the disposal of effluent to the ground, mainly the products of on-site sanitation. This represents a major source of urban recharge that is then drawn downwards in response to pumping from the deeper semiconfined aquifers. The front has penetrated to over 90 m in the most intensely pumped area (1994) although the average depth of penetration beneath the city is probably closer to 45 m.

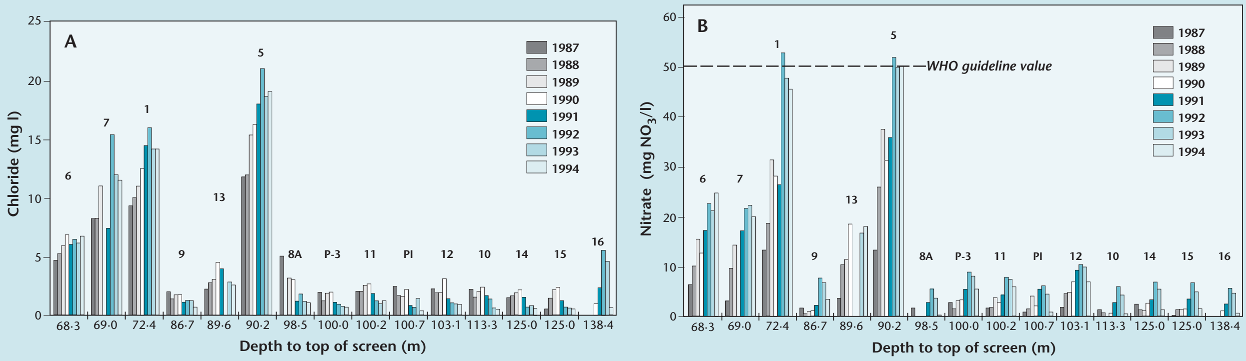
Deep groundwater abstraction first started in about 1970; by 1994 the cumulative withdrawal was equivalent to the volume of water stored within the upper 50 m of the aquifer beneath the city. This shows that the front of modern recharge is moving down at a rate of about 2 m per year and that downward leakage from beneath the city may account for the bulk of the local recharge to the deeper aquifers.




*Development of abstraction and vertical leakage in Santa Cruz aquifer system, 1971–1994.*

## BOX 25B PRIMARY AND SECONDARY WATER QUALITY EFFECTS ON DEEP GROUNDWATER IN SANTA CRUZ

The penetration and travel time of this new urban recharge can be tracked by the chloride, which acts as a tracer (Figure A) and by nitrate (Figure B). The diagrams below show how incipient contamination is starting to affect the older production wells, which have shallower depths to the top of their screened sections. By 1994, a steady rises in concentration could be observed in those wells with screens starting above 90 m depth. In a few of these shallower screened wells the nitrate content is approaching or has exceeded the WHO guideline, reflecting a trend that is likely to be occurring even more strongly in most of the (unmonitored) private boreholes in the city centre because their screens are at even shallower depths.




*Figures. Chloride (A) and nitrate (B) trends in deep public supply boreholes in Santa Cruz, Bolivia.*

Dissolved oxygen in the urban recharge is low, having been consumed as the carbon in the organic load is oxidised to carbon dioxide, which in turn reacts with carbonate minerals in the aquifer matrix to produce bicarbonate. The oxidation of the high organic load also reduces naturally occurring manganese from the aquifer matrix, making it more soluble. By 1994, the average manganese concentration in wells tapping intermediate levels of the aquifer had tripled (Figure C), with some of the older production boreholes, which have screens above 100 m, starting to show concentrations above 0.5 mg/l, leading to laundry-staining problems and an unpleasant taste to the drinking water.

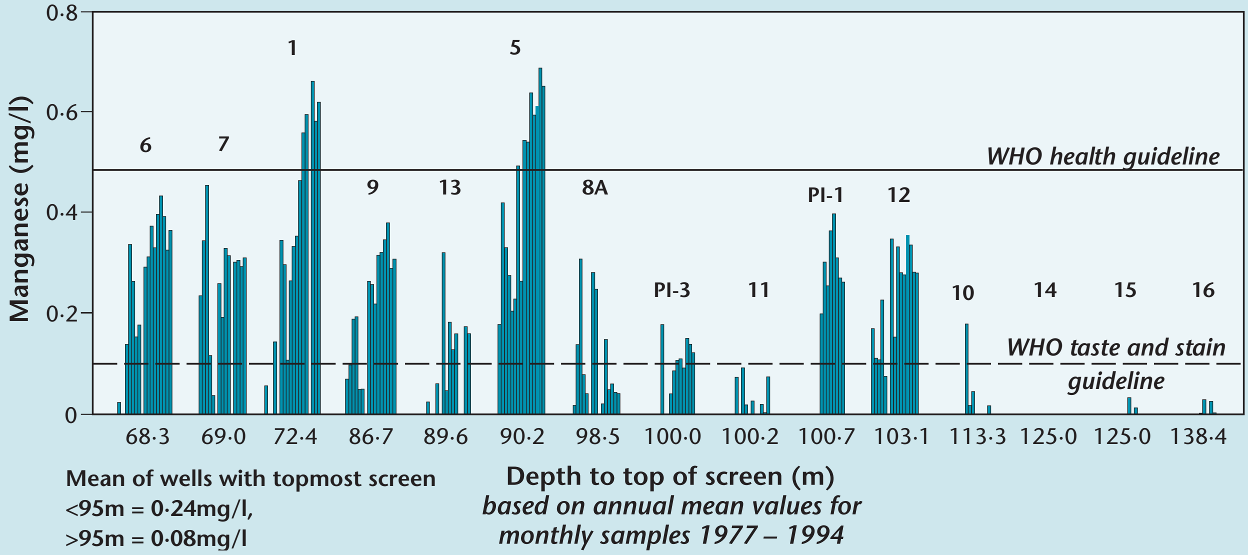



*Figure C. Rising manganese in shallower public supply wells due to urban recharge-induced geochemical changes, Santa Cruz, Bolivia.*

## BOX 26 URBAN WATER SUPPLY FROM BASEMENT AQUIFERS; EXPERIENCE FROM UGANDA

The city of Kampala and the provincial town of Iganga in Uganda obtain their water supply from weathered basement rocks. Both make extensive use of on-site sanitation. In Iganga (population 50 000), the public supply is supplemented by a large number of shallow boreholes in town, fitted with hand pumps. These wells tap an aquifer comprising an upper deeply weathered zone, some 10 to 20 m thick, overlying a more permeable fractured zone. Most of the boreholes are screened opposite the lower fractured zone (Figure A). Water sampled from these boreholes shows moderate to high nitrate concentrations but bacterial faecal indicators are largely absent. This is attributed partly to the generally low aquifer vulnerability (a consequence of the upper deeply weathered profile) and partly to the design of the boreholes; the intakes tap the deeper fractured zone where water has had a longer residence time and so had greater potential for microbial attenuation. Only the more persistent contaminants (for example nitrate and chloride derived from on-site sanitation systems) are able to reach the borehole screen. Shallower dug wells showed more frequent contamination by faecal indicator bacteria and pronounced seasonality.

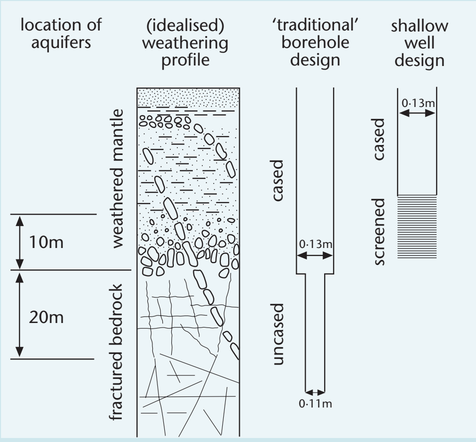



*Figure A. Urban aquifer setting in the town of Iganga, Uganda (from ARGOSS, 2002).*

By contrast, in Kampala (population about 1 million), the hilly topography has produced differential weathering, with thin mantles of weathered material on high ground discharging to springs formed at geological boundaries on the lower slopes. The aquifer supplying the protected springs thus lacks the deeply weathered zone and is characterised by shallow flow through fractured rock. There are more than 300 springs in the city and many residents who are without a domestic tap connection, use these for part or all of their domestic water needs, including drinking and cooking. The aquifer is extremely vulnerable, and tests have showed that contamination by faecal bacteria was widespread even for protected springs. The springs are replenished by local recharge, but short travel time from the ground surface to the spring outflow allows little opportunity for attenuation (Figure B).

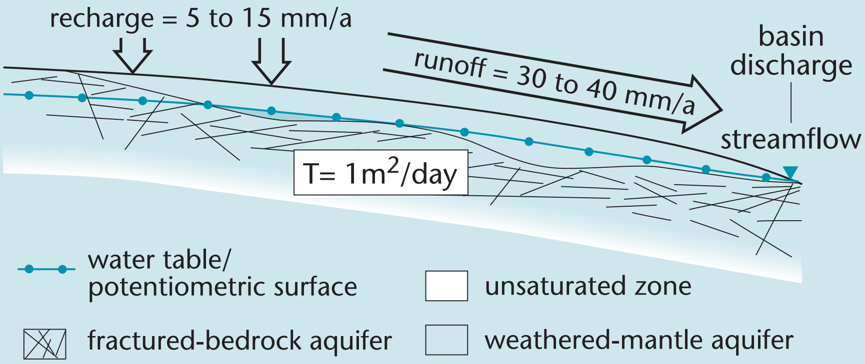



*Figure B. Groundwater flow system feeding urban water supply springs in Kampala (from ARGOSS, 2002).*

Although both urban areas rely on the same aquifer type (weathered basement) the hydrogeological setting is quite different in detail and this will affect future design of safe water and waste disposal facilities. For instance, in Kampala, an effective and well-maintained disinfection treatment stage would be obligatory rather than precautionary if the springs are to provide a bacteriologically safe water supply to the local community of low-income residents who comprise most of the users of this source of domestic water.

# IMPACT OF INDUSTRY AND MINING

6

## INDUSTRY

The literature concerning the more developed industrialised countries generally concentrates on dealing with the legacy of industrial pollution that has occurred as a consequence of over two centuries of industrial activity. By contrast in newly industrialised countries, the rate of industrialisation has been much faster (since the Second World War in many cases) and consequently the environmental damage more acute, as natural attenuation processes have not had time to make an impact on environmental recovery.

### CONTAMINANT TYPES

Most industries produce a cocktail of heavy metals, organic solvents of various types and hydrocarbons in their effluent and waste. The range of potential contaminants is vast; Table 18 shows just a representative sample.

**Table 18 Potential groundwater contaminants from common industrial operations (from Teaf et al., *In press*)**

| Industry type or industrial process | Representative potential groundwater contaminants |
|---|---|
| Adhesives | Acrylates, aluminum, chlorinated solvents, formaldehyde, isocyanates, mineral spirits, naphthalene, phenol, phthalates, toluene |
| Electrical components | Acids, aluminum, arsenic, beryllium, cadmium, caustics, chlorinated solvents, cyanides, lead, mercury, nickel, selenium |
| Explosives | Ethyl acetate, high melting explosive (HMX), methanol, nitrobenzenes, nitroglycerine, nitrotoluenes, Pentaerythritol Tetranitrate (PETN), cyclotrimethylenetrinitramine (RDX), tetrazene, tetryl, 1,3-dinitrobenzene (1,3-DNB) |
| Fabrics | Acetic acid, acetone, acrylates, ammonia, chlorinated solvents, copper, formaldehyde, naphthalene, nickel, phthalates |
| Fertilizer | Ammonia, arsenic, chlorides, lead, phosphates, potassium, nitrates, sulphur |
| Foods and beverages | Chlorine, chlorine dioxide, nitrate/nitrite, pesticides, biogenic amines, methane, dioxins, general organic wastes |
| Inks and dyes | Acrylates, ammonia, anthraquinones, arsenic, benzidine, cadmium, chlorinated solvents, chromium, ethyl acetate, hexane, nickel, oxalic acid, phenol, phthalates, toluene |
| Laundry/dry-cleaning | Calcium hypochlorite, dichloroethylene (DCE), perchloroethylene (PCE), Stoddard solvent, trichloroethylene (TCE),vinyl chloride |
| Metals production and fabrication | Acids, arsenic, beryllium, cadmium, chlorinated solvents, chromium, lead, mercury, mineral oils, nickel, sulphur |
| Solvents, chlorinated | Carbon tetrachloride, chlorofluoroethanes, dichloroethylene, methylene chloride, PCE, TCE, vinyl chloride, 1,1,1-trichloethane |
| Solvents (nonchlorinated) | Acetates, alcohols, benzene, ethylbenzene, ketones, toluene, xylene |
| Paints and coatings | Acetates, acrylates, alcohols, aluminum, cadmium, chlorinated solvents, chromium, cyanides, glycol ethers, ketones, lead, mercury, methylene chloride, mineral spirits, nickel, phthalates, styrene, terpenes, toluene, 1,4-dioxane |
| Paper manufacturing | Acrylates, chlorinated solvents, dioxins, mercury, phenols, styrene, sulphur |
| Pesticides | Arsenic, carbamates, chlorinated insecticides, cyanides, ethylbenzene, lead, naphthalene, organophosphates, phenols, phthalates, toluene, xylene |
| Petroleum refining | Alkanes, benzene, ethylbenzene, nickel, polyaromatic hydrocarbons, sulphur, toluene, xylene |
| Pharmaceuticals | Alcohols, benzoates, bismuth, dyes, glycols, mercury, mineral spirits, sulphur |
| Rubber and plastics | Acrylonitrile, antimony, benzene, butadiene, cadmium, chloroform, chromium, dichloroethylenes, lead, phenols, phthalates, styrene, sulphur, vinyl chloride |
| Wood preserving | Ammonia, arsenic, chromium, copper, creosote, dioxins, polyaromatic hydrocarbons, pentachlorophenol, phenol, tri-n-butyltin oxide |

**Table 19 Relative importance of different contaminant groups for typical industrial and other activities generating a waste load (from Calow et al., 1999)**

| Contaminant Group → / Industrial type/activity ↓ | Pathogens[A] | Cl, N[B] | Heavy metals[C] | Fe, Mn, As[D] | General organic load[E] | BTEX+ other petroleum hydrocarbons, phenols[F] | Other synthetic organics including biocides[G] | Halogenated solvents[H] |
|---|---|---|---|---|---|---|---|---|
| Food, beverages | XXX | X | X | XXX | XXX | X | XX | X |
| Textile mills, tanning, leather processing | X | XXX | XX | XXX | XXX | XX | XXX | XXX |
| Agrochemical production/storage | XX | XXX | XXX | X | X | XX | XXX | X |
| Wood processing. Paper and printing products | X | XX | XX | X | XX | XXX | XXX | X |
| Chemical/coal/petroleum/ plastic products | X | XXX | XXX | XXX | XXX | XXX | XXX | XXX |
| Iron, steel, basic metal industry | X | X | XXX | XX | X | XXX | X | X |
| Metal processing, machinery, equipment fabrication, repair workshops | X | X | XXX | XX | X | XXX | X | XXX |
| Other manufacturing industry including electronics | X | XX | XX | X | XX | XXX | XX | XXX |
| Garments and semi-finished product assembly | X | X | X | X | X | XX | XX | X |
| Retail*, commercial, government and other tertiary services | X | XX | X | X | XX | XXX | X | X |
| On-site sanitation from urban residential areas | XXX | XX | X | XXX | XXX | XX | XX | X |

Key: X Unlikely to be present in hazardous quantities XX Probably present in hazardous quantities XXX Very likely to be present in hazardous quantities
*includes fuel filling stations

Notes:
A Waterborne pathogens include disease-causing viruses, bacteria, protozoan and metazoan parasites
B Persistent major ions with WHO guideline limits
C Such as cadmium, lead, chromium, mercury, antimony
D May be naturally present in the aquifer matrix but mobilised by Eh/pH changes in the groundwater when general organic load produces anaerobic conditions, As is much the most toxic, with DWGL in _g/l while Fe and Mn have much higher DWGL limits based more on aesthetic than health criteria
E Highly variable group; aliphatics and large organic molecules from sewage and sullage, typically comprising faecal material, soaps and fats; generally less persistent than aromatic compounds
F Petrol, diesel, fuel oil including kerosene, oils, tars, gasification products. Persistence/toxicity in saturated zone depends on BTEX content
G Typically pesticides and herbicides but may include other organic compounds with WHO guideline limits such as tributyl tin oxide
H Typically chlorinated solvents such as CTC (tetrachloromethane or carbon tetrachloride), TCM (trichloromethane or chloroform), PCE (tetrachloroethene or perchlorethylene), TCE (trichloroethene or trichloroethylene), TCA (1,1,1-trichloroethane)

Many of these substances can be grouped into the eight principal inorganic and organic classes shown in Table 19 and which are likely to be present either during processing activities or in effluent/solid waste. Organic compounds of health significance, with WHO guideline limits, also arise from many industries and Table 20, which lists the most commonly encountered groups of contaminants occurring in groundwater in England and Wales is likely to be typical of many highly industrialised countries. In addition to the compounds listed in Table 19, the vast majority of industrial sites also use, and are potentially contaminated with, hydrocarbons such as mineral oils, fuels and fuel additives, which may contain the carcinogenic compounds benzene, toluene, ethylbenzene and xylene (grouped together as 'BTEX' compounds).

**Table 20 Frequently encountered organic contaminants in groundwater in England and Wales (from DEFRA, 2002)**

| Industry | Associated contaminant |
|---|---|
| Coal carbonisation | |
| Timber treatment | |
| Chemical works: dyes | Phenols |
| Textile works: dying | |
| Waste disposal | |
| Chemical works: synthesis | |
| Printing inks | Aromatic hydrocarbons |
| Coatings | |
| Degreasing agents | |
| in many industries | |
| Dry-cleaning | Chlorinated aliphatic |
| hydrocarbons | |
| Herbicide manufacture | |
| Wood treatment | Chlorophenols |
| Power stations | |
| Dockyards | |
| Railway engineering | Polychlorinated biphenyls |
| Iron and steel works | (PCBs) |
| Pesticide manufacture | |
| Fuel additives | Chlorinated aromatic |
| Pharmaceuticals | hydrocarbons |

However, it is as well to make the obvious point that by no means all industry generates large pollutant loads; compare for instance the effluent production potential of a garment-making factory with a leather works. Similarly, just because an industry employs inorganic or organic compounds in the production process it does **not** of course follow that it will be a groundwater polluter. Site- or industry-specific factors such as the method of effluent disposal, materials storage practice, the integrated pollution control (IPC) procedures in force at plants and factory sites will all influence the impact an effluent/waste-generating industry will have on an underlying aquifer.

## INDUSTRIAL CONTAMINANT BEHAVIOUR AND IMPACTS

### Behaviour of major industrial contaminant groups in the subsurface

The individual characteristics of the different industrial substances, together with the effectiveness of the various attenuation processes described in Chapter 4, influence their potential to become a widespread plume, for example as the result of a spillage (Table 21).

Physically, the groups of chemical identified in the table behave quite differently. The phenolic compounds tend to be quite soluble in water whereas hydrocarbons and aromatic hydrocarbons and chlorinated aliphatic hydrocarbons are nonaqueous phase liquids (NAPLs), so they can be present in both immiscible and dissolved phases. Fuel compounds and oils tend to be less dense than water and float, whereas the chlorinated compounds are denser and sink, with major implications for the relative penetration of the contaminant into the main part of the saturated aquifer (see Chapter 4 for an overview on the behaviour of different NAPLs).

Attenuation processes following a point source spill or leak are of variable effectiveness in reducing the concentration of contaminant entering the main body of the aquifer, depending on the types of substance involved, and this in turn affects the ability to form a widespread pollutant plume (Table 21).

The pathways to groundwater are essentially the same as those identified in Chapter 5 for the general urban setting, but derive mainly from point sources (Table 22).

### Solid waste disposal from industry and other sources

The requirement of many industries to dispose of solid wastes from processing may also have an impact on groundwater, most commonly from the infiltration of leachate from the sites. Leachate is the solution generated in a solid waste disposal site due

**Table 21 Attenuation processes in the aquifer unsaturated and saturated zone for various contaminant groups following a point source spill**

| Contaminant group | Examples | WHO guideline concentration | Attenuation processes: Degradation | Dilution** | Sorption | Filtration | Potential to become widespread plume | Comments/rationale |
|---|---|---|---|---|---|---|---|---|
| Pathogens† | Faecal coliforms‡ | 1 FC/100 ml | ✓✓ | ✓✓ | ✓✓ | ✓✓ | Low | Generally attenuated over short distances (except in highly fractured aquifers) |
| | N as NO‡ | 50mg/l | ✓ | ✓✓✓ | X | X | Moderate | Highly mobile and persistent, but high DWGL* requires very large loading such as from widespread on-site sanitation or saline intrusion to produce widespread problem |
| Anions | Cl | 250 mg/l | X | ✓✓ | X | X | High | |
| Heavy metals | Cr, Hg, Cd | mg/l | X | ✓✓ | ✓✓✓ | X | Low | Metals usually sorbed unless pH either very high or very low |
| Secondary quality problems (Eh/pH control) | Fe, Mn, As | mg/l | X | X | ✓✓✓ | X | Low | Extent likely to be small except in anaerobic or low pH groundwaters |
| BTEX | Benzene | 10 µg/l | ✓✓✓ | ✓ | ✓✓ | X | Low to Moderate | Light BTEX relatively easily degraded in aerobic systems; heavier BTEX generally sorbed. Both amenable to biodegradation; spillage volumes may however be large |
| General organic load† | DOC§ | mg/l | ✓✓✓ | ✓✓ | ✓✓ | X | Low | Difficult to generalise |
| Other synthetic organics | Pesticides | Various in µg/l | ✓✓ | ✓✓ | ✓✓ | X | Moderate | |
| Halogenated solvents | PCE | 40 µg/l | ✓ | ✓ | ✓ | X | High | Low permitted DWGL*; potentially large mass (if present as immiscible phase) and persistence in groundwater all favour large plume development |

Notes: Attenuation process: ✓✓✓ major importance ✓✓ important or highly variable ✓ minor importance X Not applicable
* DWGL: WHO Drinking water guideline limit † Not normally monitored ‡ Faecal coliform counts are used as pathogen indicators § Indicator
** Dilution ratio = Potential mass spilled divided by drinking water guideline value

Process classification key: Degradation: ✓✓✓ $^1/_2$ life < 1 month ✓✓ $^1/_2$ life > 1 month< 1 yr ✓ $^1/_2$ life > 1 yr
** Dilution ratio ✓✓✓ <1010 ✓✓ 1010 – 1012 ✓ ratio > 1012

Potential to become a widespread plume:
High Contaminants have potential to remain long term contaminants and produce large/dispersed plumes
Moderate Contaminants are attenuated in aquifer but significant plumes above DWGL may persist
Low Contaminants easily attenuated (degraded, sorbed or filtered) such that concentrations readily reduced to tolerable levels

**Table 22 Common sources of groundwater pollution from industry**

| Source | Mechanism or main contributory factors |
|---|---|
| Underground and surface storage tanks, process and effluent pipe work or other transfer system | Undetected leakage or inadequate bunding to retain major failures |
| Industrial sewers/collectors | Leakage through poor maintenance |
| Soakaways, waste injection wells | Pollution through inappropriate disposal practice |
| Bulk chemical storage areas | Poor handling and storage procedures, leaks |
| Liquid effluent and process lagoons | Leakage through poor construction/maintenance |
| Solid process waste disposal sites | Leakage of leachate through poor construction or failure of design |
| Accidental/catastrophic discharge | Plant fire, explosion, impact and loss of material to ground |

to the release of moisture during waste decomposition together with components dissolved in infiltrating rainwater. Waste composition influences the chemistry of the leachate generated. A very high content of putrescible material coupled with a low content of recyclable material such as glass, paper and metals is typical of the wastes in newly industrialised countries. The widespread practice of informal recycling of waste, such as glass and cans, may explain to some extent the very high organic matter content present in the disposed wastes of newly industralised countries.

There are three broad phases of waste decomposition:

- *aerobic decomposition* which rapidly consumes any oxygen present and produces heat;
- anaerobic decomposition of complex carbohydrates and cellulose to soluble simpler organic compounds – the *acetogenic phase*, in which the leachate has a low pH, with the potential to mobilise heavy metals, and contains a high concentration of volatile fatty acids and ammoniacal nitrogen;
- decomposition by methanogenic bacteria – the *methanogenic phase*. This consumes the simple organic compounds producing a mixture of methane and carbon dioxide as gas. The remaining leachate contains high molecular weight organics, such as humic acid. Falling redox potential immobilises many metals as sulphides in the waste.

Leachate from waste is therefore a highly mineralised mixture of inorganic and organic compounds consisting of four principal groups of pollutants:

- dissolved organic matter expressed either as chemical oxygen demand (COD) or total organic carbon (TOC); it includes methane and volatile fatty acids;
- organic compounds derived from industrial and household wastes, for example aromatic hydrocarbons and phthalate esters;
- inorganic macro components, for example calcium, sodium, potassium, chloride, ammonium, sulphate;
- heavy metals, for example chromium, copper, nickel, lead, manganese and cadmium.

It is often difficult in practice to distinguish contamination products from industry alone because in many countries, solid waste sites receive both industrial and household (domestic) wastes for co-disposal. Sewage sludge is often a hazardous component of waste and may consist entirely of raw sewage from septic tanks or the sludges from a treatment plant dealing with effluent from an industrial collector. Indeed, recent work in Mexico has clearly demonstrated the potential for waste leachate to be a significant source of sewage-derived pathogens.

The volume of leachate produced depends both on the composition of the waste and the volume of infiltrating water. In humid tropical conditions leachate can be generated in relatively large volumes because of the higher recharge regime (Box 27), making leachate plumes relatively extensive.

The other waste stream typically disposed of to ground is that from domestic users. A review of

### BOX 27 SOLID WASTE DISPOSAL IN CHIANG MAI, THAILAND

Chiang Mai, the second largest city in Thailand, relied on open dumping of solid waste at the Mai Hia site for over 30 years. The waste had a high organic and water content with potential for high total organic carbon (TOC) leachate production. A well-developed plume of contaminated water to the east of the site led to its closure in 1989. A later study found evidence for pulses of contaminants still moving away from the site during the rainy season. During the dry season, conditions are anaerobic, with nitrate only present at a few points and widespread detection of iron and manganese in the aquifer.

Piped water from elsewhere has now been supplied to local villagers, but local well water is still used in some of the poorest households. A risk assessment using two examples of concentrations detected demonstrated that DEHP (diethyl hexyl phthalate, WHO-DWGL 8 µg/l) could present an unacceptable carcinogenic risk and manganese an unacceptable toxic risk to local groundwater consumers.

*(from Karnchanawong et al., 1993 and Klinck et al., 1999)*

### BOX 28 PESTICIDES IN SOLID WASTE DISPOSAL SITE; HELPSTON, ENGLAND

A significant amount of waste pesticides was disposed to two sites accepting putrescible waste into disused quarries on the Lincolnshire Limestone of Eastern England. One producer alone had disposed of some 40 tonnes of agrochemical wastes. This led to the detection of the phenoxy acid herbicide mecoprop at concentrations between 1 and 3 µg/l in groundwater abstracted at a public supply borehole some 2 km away. The UK and WHO-DWGL standards are 0.1µg/l and 10 µg/l for drinking water. Further study detected up to 30 000 µg/l of mecoprop in groundwater close to the point of disposal. Localised faulting and zones of anaerobic groundwater where little mecoprop degradation takes place have contributed to the high concentrations arriving at the pumping station

*(from Sweeney et al., 1998).*

### BOX 29 HALOGENATED SOLVENTS:THE UK EXPERIENCE (FROM TEAF ET AL., IN PRESS)

As with refinery sites, large and small halogenated solvent sites around the world have been associated with groundwater contamination. This is as a result of their historical widespread use for degreasing, metals cleaning, textile treatments, and other applications. Although these solvents exhibit comparatively low water solubility, their environmental behaviour as Dense Non-Aqueous Phase Liquids (DNAPLs) often causes disproportionate problems when engineering remediation solutions. In addition, many countries have established quite restrictive water quality protection criteria for halogenated solvents (for example trichloroethylene, perchloroethylene) or potential environmental degradation products (for example, vinyl chloride). A case which has elements reminiscent of many others involved the Cambridge Water Company and several local tanneries in the United Kingdom during the 1950s through the 1990s.

Trichloroethylene (TCE) and tetrachlorethylene (perchloroethylene or PCE) are among the most common halogenated solvents encountered, and were used in the leather tanning process. On-site handling practices, as well as spills and other releases, caused soil contamination at this industrial site. The complex geology in the area (multilayered Chalk limestone) complicated several efforts to model the contaminant flow in the vertical and horizontal direction. However, it was concluded that the releases probably occurred in the early years of solvent use at the facility (i.e. the late 1950s). Discovery of contamination at a local water supply borehole in the early 1980s triggered an extensive investigation by the local Water Authority and the British Geological Survey, which ultimately demonstrated significant contamination, broadly distributed in the area at concentrations exceeding 1000 µg/l. Despite conversion of the local water supply borehole to a pump-and-treat recovery well (which retrieved over 3600 litres of PCE in five years), a substantial quantity was unrecoverable, as is often the case with the halogenated solvents.

Although there is a tendency to focus on large industries as being more likely to cause large groundwater impacts, the legal discussion surrounding this case emphasized the potential for contributions to local groundwater pollution by many small industries in an area. Also the valuable benefits of planning and proper chemical handling, as opposed to attempting remedial actions decades after the release has occurred. Of course, this observation can be made for other industries as well, including, for example, textile operations, tanneries, motor vehicle fuel stations and electroplating shops.

**Table 23 Hazard features of principal industrial and other contaminants posing a threat to underlying groundwater**

| Contaminant Group[1] | Persistence[2] | Mobility[3] | Toxicity[4] | Filtering capacity of soil/unsat. zone[5] | Assessment criteria and units[6] | Guide limit for potable quality[7] |
|---|---|---|---|---|---|---|
| Pathogens[A] | X | XX | XXX | XXX* | Faecal coliform count/100ml | |
| Cl, N[B] | XXX | XXX | X | X | concentration mg/l | Many individual values; refer to WHO or local guidelines |
| Heavy metals[C] | XXX | X to XXX | XXX | X | concentration µg/l | |
| As (also Fe, Mn, posing minor hazard) [D] | XXX | X to XXX | X | X | concentration mg/l | |
| General organic load[E] | X to XX | X to XX | X to XX | X | BOD, COD concentration mg/l | |
| BTEX+ other petroleum hydrocarbons, phenols[F] | X to XX | XX | XX to XXX | X | concentration µg/l | |
| Other synthetic organics inc biocides[G] | X to XXX | X to XXX | X to XXX | X | concentration µg/l | |
| Halogenated solvents[H] | XXX | XXX | XXX | X | concentration µg/l | |

Key: X Low XX Moderate XXX High

Notes: A, B. C, D, E, F, G, H See contaminant group notes in Table 20

1. Groupings which reflect either features in common, similar provenance or similar behaviour in the subsurface
2. Indicator of ability to remain in the same form
3. Indicator of relative inability of subsurface to retain or attenuate by processes such as dispersion, sorption, cation exchange, precipitation, hydrolysis, complexation, biologically mediated transformation
4. General indication of toxicity of entire group or important group members using WHO/EU drinking water guidelines
5. Indicator of ability to detain contaminant by physical process of filtration
6. Indicators which can be used to assess whether contaminant group likely to be present or as measure of contamination severity
7. Guide to severity of contamination if the contaminant group should be detected, referenced to use for drinking water

* Excludes viruses

leachate composition from sites accepting domestic wastes in the UK concluded that ammoniacal nitrogen has the greatest potential to adversely impact on surface and groundwaters near to disposal sites. Heavy metals are not generally present at significant concentrations. The most frequently detected compounds are chlorinated aliphatic compounds, chlorobenzenes and BTEX. However, potentially hazardous organic compounds detected included the triazine herbicides, lindane and organotin compounds. Disposal of pesticides to solid waste sites can lead to major groundwater pollution problems (Box 28).

**Assessing and prioritising threats from industry to vulnerable groundwater**

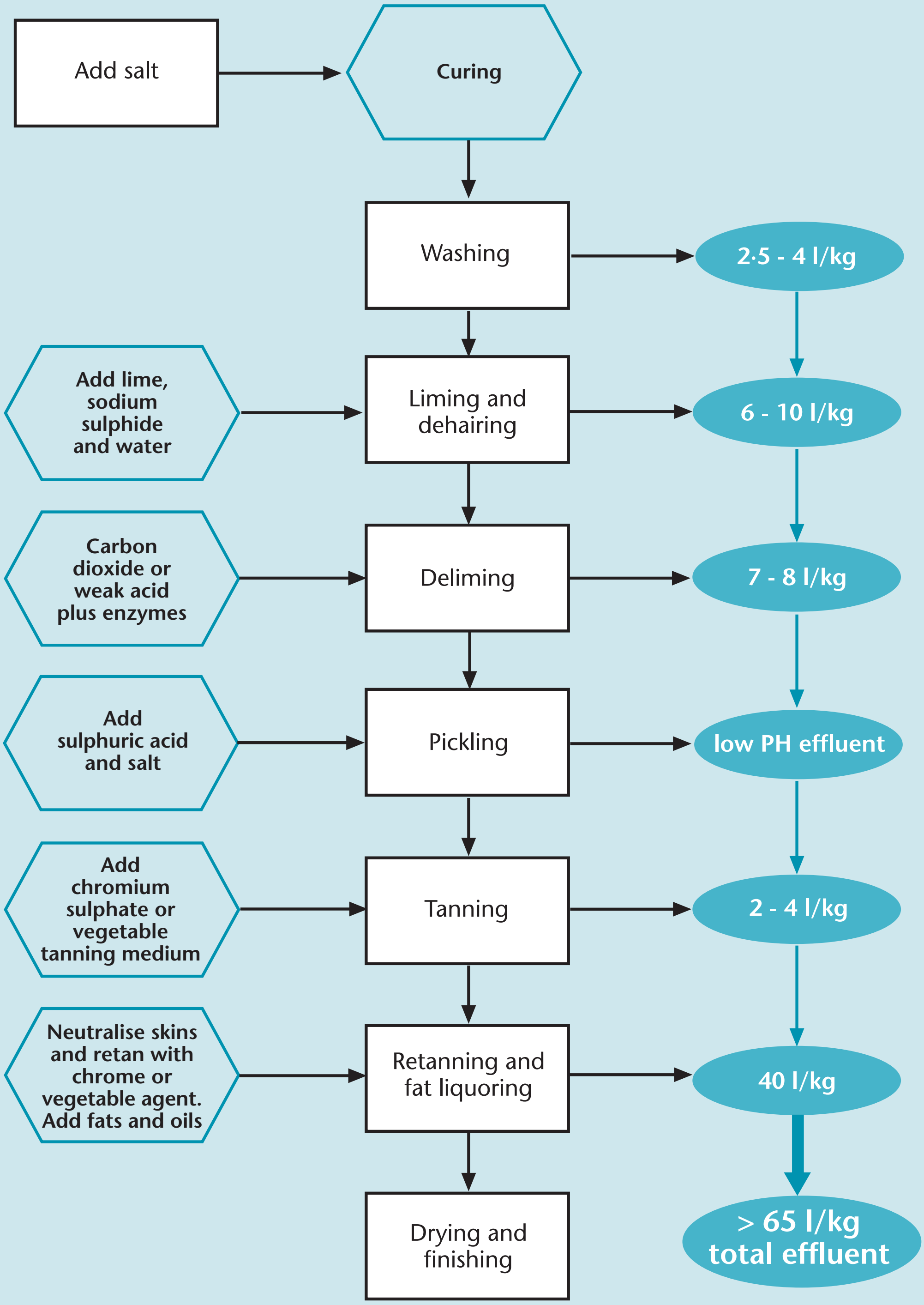
An additional feature important to recognise when assessing groundwater vulnerability is the ubiquitous nature of much industry. Where heavy industry is concentrated in designated industrial zones, dedicated facilities for industrial effluent collection/treatment and solid waste collection/disposal can be designed into the zone's infrastructure. However, much light industry and most small workshops are dispersed, typically located adjacent to or within city residential and commercial areas or on the edge of smaller urban centres where separate sewerage or specialist waste disposal facilities may not be practicable or available. This is a pattern seen in the older industrial countries and emerging economies alike.

Where such activities are located on vulnerable aquifers, preventive measures are extremely important to minimise the likely contaminant load, but it must be accepted that some contamination by accident or design is inevitable. Coping strategies therefore need to identify and prioritise the most important threats to the use of the underlying groundwater for sensitive purposes.

Typically groundwater used for drinking water supply is the most sensitive and Table 23 summarises the hazard features of the eight important contaminant groups likely to pose a threat to underlying groundwater.

## BOX 30 STAGES IN THE TANNING PROCESS

A number of stages are involved in the tanning of raw hides, at each stage of which various chemicals are added and effluents of different compositions produced. The flow diagram illustrates the general sequence of stages of a typical tanning process. The effluents produced contain chromium (a potentially toxic heavy metal), sodium chloride (a potential cause of salinisation) and alkalis and acids (potentially able to modify aquifer geochemical conditions and thereby mobilise other contaminants).




*Typical tanning process for leather.*

**BOX 31 GROUNDWATER POLLUTION DUE TO LEATHER INDUSTRIES: EXAMPLES FROM INDIA AND MEXICO**

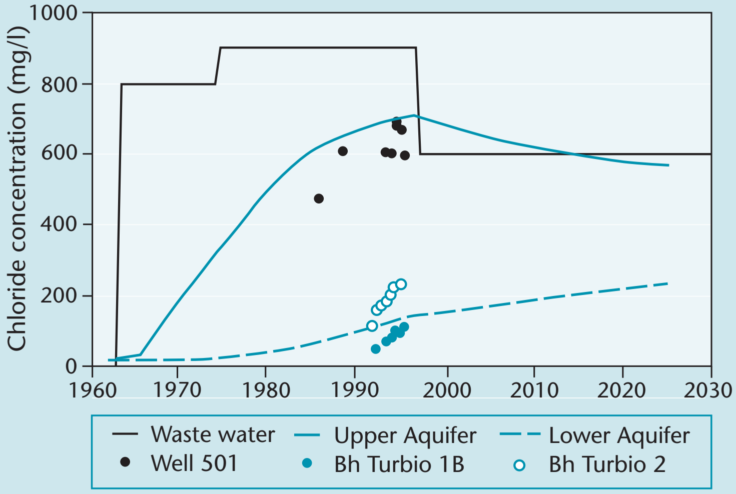
*Tamil Nadu, India (from Muthu, 1992)*
India produces about 13 per cent of world output of hides and skins. Effluents from tanning processes typically have a high biological oxygen demand (BOD), high chloride, may contain calcium and ammonium salts, and, depending on the particular process used, also high concentrations of trivalent chromium. In 1994, tanneries in the state of Tamil Nadu accounted for about 60 per cent of Indian production. They were concentrated into a few centres near to Madras, the state capital, on the banks of the Palar and Kundavanuru Rivers. These initially perennial rivers supplied the large amounts of water for the tanning process and also acted as receptors for discharged effluent. Ecosystem and other changes mean the rivers are now seasonal and this has prompted greater reliance on groundwater for processing while effluent continued to be discharged to the dry river beds.

The declining availability of surface water for potable supply demands also stimulated use of shallow groundwater, which was available at depths of 9 to 12 m. However, effluent seepage to groundwater from the dry river channels has caused widespread contamination of the shallow aquifer, usually manifested as an increase in salinity and hardness. As a result, a whole new industry has arisen, dedicated to tankering in fresh water from uncontaminated areas. Continued high demand from tanneries for clean water has led to intense competition between industry and local domestic consumers, leading to inflated prices for groundwater of potable quality.

*León, Mexico (BGS et al., 1996, Klinck et al., 1995)*
The city of León-Guanajuato in central Mexico, which has one of the most prominent leather industries in Latin America, was said to have more than 500 leather curing and tanning establishments in the early 1990s. Disposal of solid tannery wastes occurs both at factory sites and at municipal refuse sites.

In the former, leachate from the waste had polluted groundwater in an area of about 5 $km^2$ resulting in concentrations of up to 50 mg/l of hexavalent chromium (WHO limit 0.05 mg/l). The groundwater plume shape and extension appear to be controlled by the prevailing groundwater extraction regime indicating that future impacts may occur on some production wells. The municipal landfill had been in operation since 1986 and accepted municipal, domestic, medical and industrial waste including tannery wastes. Leachate chromium content was found to be 5.43 mg/l. Modelling of the site suggested transit times to the water table below the site of between 2 and 11 years, ignoring any induced recharge due to nearby groundwater pumping.

Municipal waste water from the city also contains tannery effluent and is used for irrigation in the Leon valley. As well as chromium, the waste water has a high chloride content from the desalting of cured hides. Although the soil zone detains chromium dissolved in the waste water, saline recharge from over-irrigation threatens municipal water supply boreholes located in rural well fields within and adjacent to the waste-water irrigated area. Modelling of options to manage the problem shows that salinisation trends in the aquifer will be slow to respond even with major remedial measures.




*Predicted future salinisation trends in municipal water supply well field in León, Mexico, assuming both interception pumping from the upper aquifer and treatment of industrial effluent.*

Pathogens for instance, although of major health significance, die off with time and so only pose a major threat in those aquifers where residence time is so short that attenuation due to physical or biological processes such as filtration and predation has not had time to occur before abstraction. In contrast, filtering is ineffective in detaining halogenated solvents, whose high mobility, persistence and toxicity at low concentrations pose a major threat to groundwater used for drinking water supply, especially if minimal treatment is envisaged.

The acceptable end-use of the water also influences the magnitude of the threat posed by a given industrial contaminant. Thus processes generating salinity (such as hide washing in leather processing or caustic soda production) may readily result in chloride contamination. Although poorly attenuated by aquifer processes other than dilution, the high chloride threshold values for serious health or agricultural impacts mean that compared with for instance halogenated solvents, much higher quantities can enter the aquifer below a site before salinity poses a major threat.

Another aspect of impact assessment of an industrial contamination event to consider is response time. Different aquifer settings not only vary in their attenuation ability but also have different timescales within which a response to a pollution episode can be

**Table 24 Assessing how soon effects of problem contaminant group are likely to affect the user/user group**

| Hydrogeological environment | Typical range of groundwater lateral velocities $V_h$ (km/a). Vertical velocities typically 1%-10% of $V_h$ | Typical time needed for contaminant to move 1 km laterally or 100m vertically from source to abstraction | Likely attenuation capacity of aquifer system during transit | Indicative response time available before contaminants threaten use/user group |
|---|---|---|---|---|
| Major alluvial/coastal plain sediments | 0.0001-0.1 | Decades to millennia | High | Long |
| Intermontane systems: | | | | |
| colluvial/alluvial | 0.0001-0.1 | Decades to millennia | High | Long |
| volcanic/volcanosedimentary | 0.01-1 | Years to centuries | Low to moderate | Medium |
| Glacial and minor alluvial formations | 0.01-1 | Years to centuries | Moderate | Medium |
| Loessic plateau deposits | 0.0001-0.1 | Decades to millennia | High | Long |
| Consolidated sedimentary aquifers | 0.1-10 | Months to decades | Low to moderate | Short |
| Recent coastal calcareous formations | 0.1-10+ | Days to months | Low | Short |
| Extensive volcanic terrains | 0.01-10+ | Days to centuries | Low to moderate | Short to medium |
| Weathered basement complex | 0.01-1 | Years to centuries | Low | Medium |

Notes: Response times cited assume that contaminant is likely to be present as point or linear source and located up-gradient of user group wells/abstractions. Contaminants present as diffuse sources, or as multiple closely spaced sources verging on diffuse, would tend to reduce available response time:

Short <1 year; fast response required if use/user group to be protected; options greatly constrained
Medium 1-10 years; moderate time available to respond; more options available
Long >10 years; ample time available to exercise options but prompt response will maximise opportunities for chosen option to work

formulated. These timescales are functions of the aquifer size, geometry, type of flow and the nature of the rock matrix.

Table 24 summarises the typical range of available response times for eight major groundwater settings, although it must be stressed that each pollution scenario is unique and local factors may be present which will over-ride the indicated ranges, which are generalised values only. As ever, there is no substitute for a competent site investigation when dealing with a particular groundwater contamination episode.

Boxes 29, 30 and 31 use examples from the leather processing industry to illustrate the sustainability issues facing groundwater from some industrial processes.

## MINING

### NEED FOR PLANNING TO ANTICIPATE ADVERSE GROUNDWATER EFFECTS DURING AND AFTER MINING

Mining and opencast workings can impact the environment via a variety of chemical and physical routes, many of which are at their most critical phase during the post-closure operation of a mine. Sources, routes and receptors are summarised in Table 25.

Mining is an important contributor to the economies of many newly industrialised countries as well as a diminishing number of the older industrial economies. Moreover, mining is very much in the public consciousness as an activity that is perceived to give rise often to serious environmental pollution. In many newly industrialised countries, the hazards posed by both active mine wastes and by residues at abandoned mine sites are especially acute as regulatory controls and environmental legislation may not be in place or be weakly enforced.

**Table 25 Groundwater problems arising from mining activities**

| Mining activity, process or consequence | Potential effect on subsurface if design inadequate | Resultant environmental problem |
|---|---|---|
| Mine drainage<br>acid mine drainage | Mine water rebound | Groundwater/surface water pollution from |
| Mine gas generation | Migration through strata | Mine gas emission at surface |
| Shallow mining | Ground instability | Subsidence |
| Deep mining | Enhanced transmissivity above workings due to collapse fractures | Localised dewatering of overlying aquifer, or intrusion of lower quality water on rebound |
| Tailings lagoons | Effluent seepage | Pollution plumes |
| Waste rock dumps | Acid and metal rich leachate | Pollution plumes below tailings |

It is when major disasters occur that mining-related hazards are brought to public attention and highlighted by the media. Perhaps one of the most high profile events was the much publicised Aznacollar tailings dam failure in Spain which threatened the entire ecosystem of the Doñana National Park. The failure of the Aznacollar mine settling pond on April 25th, 1998, resulted in the discharge of 6 million $m^3$ of sludge and acidic water with a pH of ~5.5 and high concentrations of heavy metals. An area of approximately 46.3 $km^2$ was affected and 62 km of river bank and underlying

**BOX 32 ‘NO BASTA DECIR ADIOS’ (IT’S NOT ENOUGH TO SAY GOODBYE)**

This laconically titled article in the Chilean magazine *Induambiente* (1999) observes that there are more than 800 abandoned tailings facilities in Chile that have not been properly closed down. Juanita Gonzalez, External Assessor of the Chilean National Environment Commission CONAMA is quoted as saying: ‘Alguien tiene que hacerse cargo de ellos y de determinar si existe un riesgo real’ (Someone has to take charge of them and determine if there is a real risk).

**Table 26 Examples of defensive mine planning measures (based on hydrogeological and geochemical principles) applicable at different stages in the life-cycle of a mine (from Younger and Robins, 2002).**

| Stage in mine lifecycle | Proposed measures | Relevance to long-term environmental performance of mined system |
|---|---|---|
| Exploration | Assay the overburden for long-term pollutant release potential | Allows minimisation of long-term water quality liabilities by careful handling |
| | Ensure adequate after-use of exploration boreholes, either b associated with site drainage<br>(a) efficient back-filling and sealing or<br>(b) by equipping them for hydrogeological monitoring purposes | (a) Minimisation of long-term water make, and therefore of liabilities<br>(b) Acquisition of pre- and syn-mining hydrogeological data to allow full assessment and planning of mitigation measures for any water management problems arising from dewatering and / or mine abandonment |
| Detailed design | Plan pillar locations and geometry of major mine access features to facilitate easy blocking of potential post-abandonment hydraulic pathways | Minimisation of deep circulation of waters after mine closure, which should help to limit rock-water interaction residence times and therefore keep salinities as low as possible |
| Site preparation | Construct mine access features consistent with detailed design | Minimises post-closure costs to achieve management objectives |
| | Locate mineral processing and tailings / waste rock storage facilities in those portions of the site least likely to give rise to environmental pollution in emergency situations | Achieves compliance with standard water quality protection policies of regulators; will also make eventual decommissioning less expensive to achieve |
| Main phase of extraction | Careful design of panels / pillars / benches to minimise the inducement of excess water inflow from surrounding strata | Minimises water make and all associated costs |
| | Local 'over-dosing' with calcite stone dust and / or topical grouting of high-S / high-K zones to minimise later pollutant mobilisation | Minimises mobilisation of acidic ions in mine water after mine is flooded |
| Mine waste management | Make provisions for selective handling / careful disposal of the most pollution-generating waste rock (using methods such as co-mingling with reductants / alkalis, $O_2$ exclusion, by means of water covers/ dry covers etc) | Pre-empts possible future water quality liabilities, which would likely be very long-term in nature |
| Mine abandonment | Engineer any long-term preferred drainage routes for 'permanence' | Ensure long-term drainage routes are predictable and reliable |
| | Seal major mine access features at or just below anticipated climax water table position | Minimise deep circulation (and therefore salinisation) of mine waters |
| | Consider the installation of (?replaceable) in situ reactive media in main shafts / declines to provide treatment of polluted drainage prior to surface discharge | Maximise the potential for emergence of good quality water at the ground surface |
| | Ensure facilities are in place for monitoring of rebound and climax water table positions | Secures long-term monitoring to allow early identification of any problems / demonstration of system stability to third parties |
| Restoration | Ensure that hydrological issues are given suitable prominence in restoration plans for underground voids and mine waste depositories | Minimisation of long-term pollutant release through restricting access to acid-generating materials by $O_2$ and / or $H_2O$ |
| | Involve all relevant stakeholders in financial and institutional arrangements for post-closure site maintenance and monitoring activities | Establishment of a secure socio-economic foundation for long-term site management / after-use |
| | implement any short-term intensive water treatment measures during the 'first flush' | Avoids any legal problems during the period of most elevated pollutant concentrations |
| After-care | Implement post-closure site maintenance and monitoring activities | Achieve stable post-closure water management system |
| | Implement long-term (?passive) water treatment measures as appropriate | Ensure long-term attainment of water quality objectives in receiving watercourse |

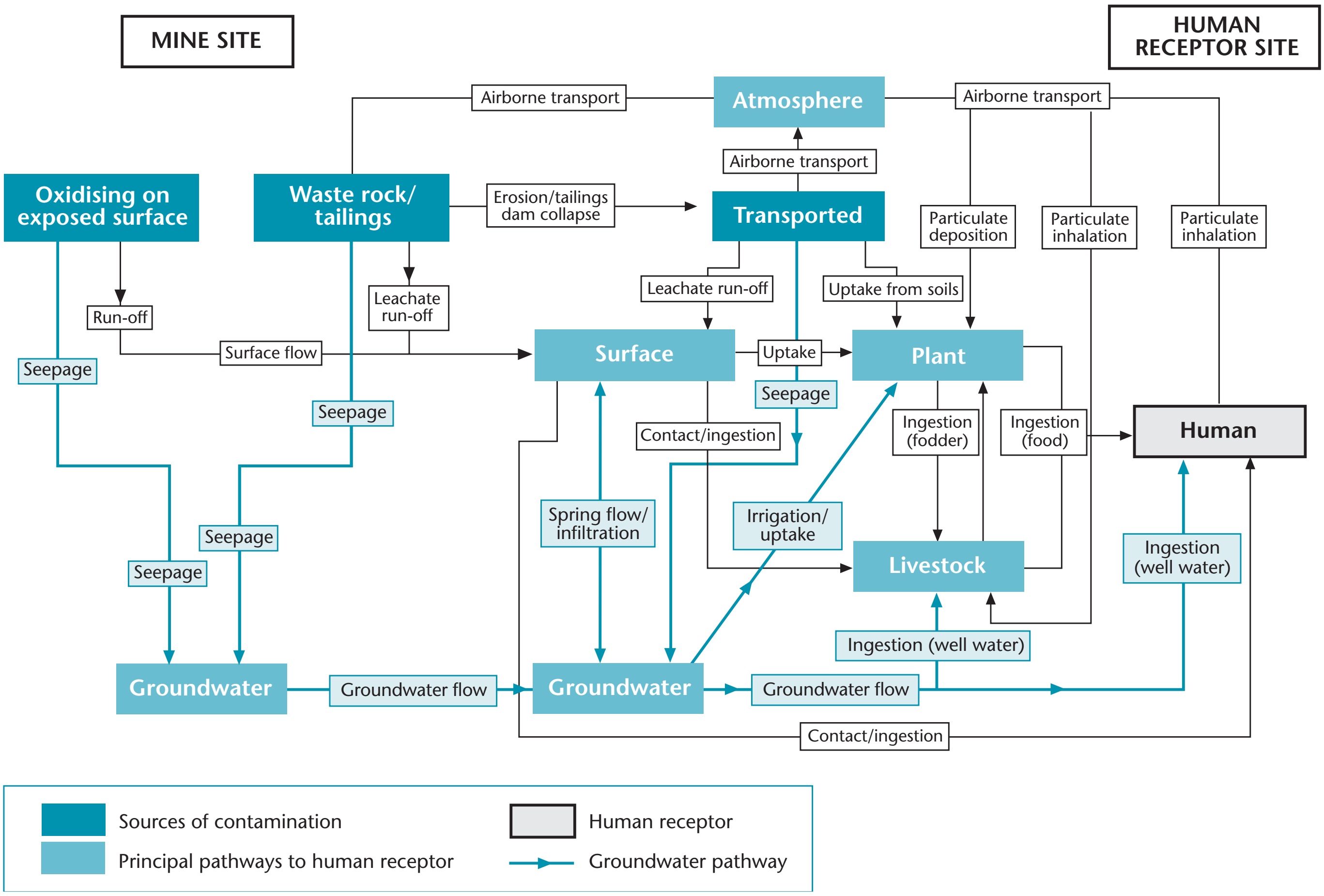



*Figure 20. Main pathways of mining contamination to a human receptor. The groundwater pathway is shown in blue. (from Klinck et al 2002).*

alluvial aquifer was contaminated to an average width of 500 m, extending to the north-west limits of the Doñana National Park. This event constituted an environmental catastrophe on a scale never before seen in Europe.

It is important that the lessons learnt from experience with the now declining mining interests in Europe and North America are heeded in the development of new mines in other continents. Simple guidelines (Table 26) if applied during the exploration and development phase of a mine can ultimately save resources during the operation and subsequent closure of the mine. These guidelines aim to safeguard the environmental assets (and health interests) of the surrounding region and its communities.

## EXAMPLES OF EFFECTS ON GROUNDWATER OF MINING ACTIVITIES

**Water quality effects**

Figure 20 shows schematically the main sources of contaminant inputs to groundwater due to mining activities.

The main water-associated environmental health hazards deriving from mines and mine tailings arise from the discharge of acid mine drainage (AMD) to surface and groundwater (see Box 33), and the contamination of soils through related industrial activity. Abandoned mines, tailings piles and associated, untreated, acid mine drainage constitute an important source of heavy metal contamination to the geosphere. The mining of tin provides good examples of the kinds of problem that can be encountered (Boxes 34 and 35).

**Effects on water levels**

In recent years, there have been a few investigations, mostly in the USA, into the adverse effects of deep coal mining on both surface watercourses and groundwater levels. These can arise for several reasons:

i The mine may underlie a productive aquifer within the general sequence containing the coal horizons. Dewatering of the workings may then induce depression of water levels in overlying beds used for water supply.

ii The coal-producing strata may be quite distinct from the overlying aquifer, separated by various beds of low permeability or by thick strata. However, long-term dewatering may induce leakage through the intervening aquitard and then the overlying aquifer, causing depression of potentiometric water levels in the latter.

iii The physical disturbance and removal of material, especially in longwall operations, may cause subsidence and associated fracturing of overlying beds, either increasing locally the transmissivity of an existing aquifer or even, in extreme cases, creating a productive aquifer out of poorly permeable consolidated strata.

For example, in a West Virginia mine, workings at depths of 52 to 117 and 122 m caused monitoring wells and surface springs to become dry. In Illinois workings at a depth of 122 m caused a decline of up to 30 m in the potentiometric surface of an overlying sandstone aquifer. This was accompanied by permanent post-mining increases in the aquifer hydraulic conductivity of up to 1900 per cent of its original value, while during mining, temporary increases of an order of magnitude were observed. A similar effect has been observed in the UK (Box 36).

*References*
*Bibliography (pp.120-125) numbers 7, 10, 12, 13, 15, 30, 32, 33, 34, 40, 42, 44, 55, 59, 63, 65, 68, 69, 70, 86, 88, 91, 98, 101, 103, 104, 105, 107, 116, 117, 118, 119 and 124 have been used in the production of this chapter.*

**BOX 33 THE DEVELOPMENT OF ACID MINE DRAINAGE (AMD) FROM PYRITE**

Acid mine drainage forms when pyrite, a commonly occurring mineral associated with the metal ore in the vein, oxidises and then passes into solution. The reaction passes through several stages. In the first reaction, (the initiator reaction) pyrite oxidises in the presence of moisture and oxygen to generate ferrous ions and protons (i.e. acidity). The ferrous ions can then oxidise to produce ferric ions, which are responsible for the red water colouration of drainage and also for the red ochre precipitates often seen on stream beds affected by acid drainage.

Once present in the system the ferric ions can oxidise more pyrite to produce more sulphate and protons. These reactions are favoured in the moist oxidising conditions of waste rock piles and mine workings. The problem of acid mine drainage is further compounded when other metals are mobilised from the wastes, such as arsenic and aluminium.

## BOX 34 CONSEQUENCES OF MINE WATER REBOUND: WHEAL JANE TIN MINE, ENGLAND

The south-west corner of England is rich in minerals and has been mined for hundreds of years. Wheal Jane was one of many shallow mines in the area, producing tin, copper, zinc and lead. The mine was extended at various times but the collapse of the tin price in 1985 prompted its eventual closure in March 1991, by which time the workings extended to over 500m below ground level (Figure A).

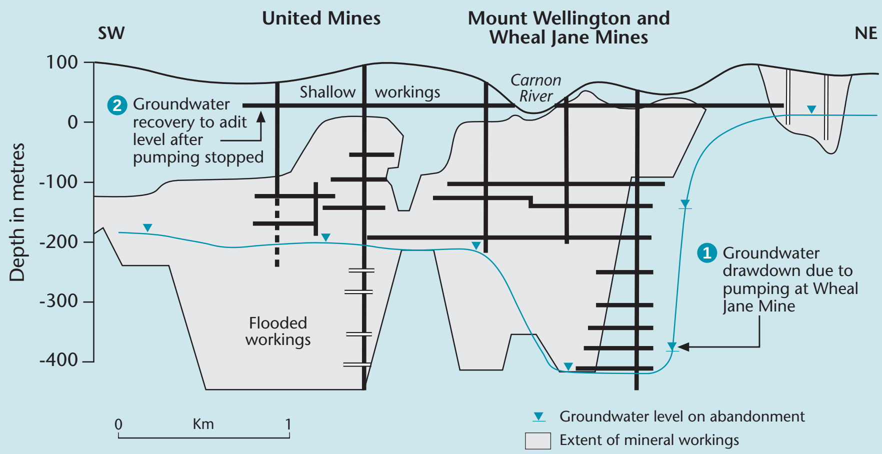



*Figure A. Schematic cross-section of Wheal Jane and adjacent mines (from NRA, 1994).*

The mine and its neighbour to which it is linked underground had been kept dry by a massive dewatering operation, and when pumping ceased the acidic water in the mine (containing significant concentrations of metals including cadmium, zinc, nickel, arsenic, copper and iron) rose. Discharges of the rebounding groundwater started in November 1991, exacerbated by the failure of an old adit plug adjacent to the Carnon River which led to the release of million of gallons of contaminated mine water in January 1992. Figure B shows the impact on the Carnon River between November 1991 and May 1992 for the two contaminants of cadmium and zinc.

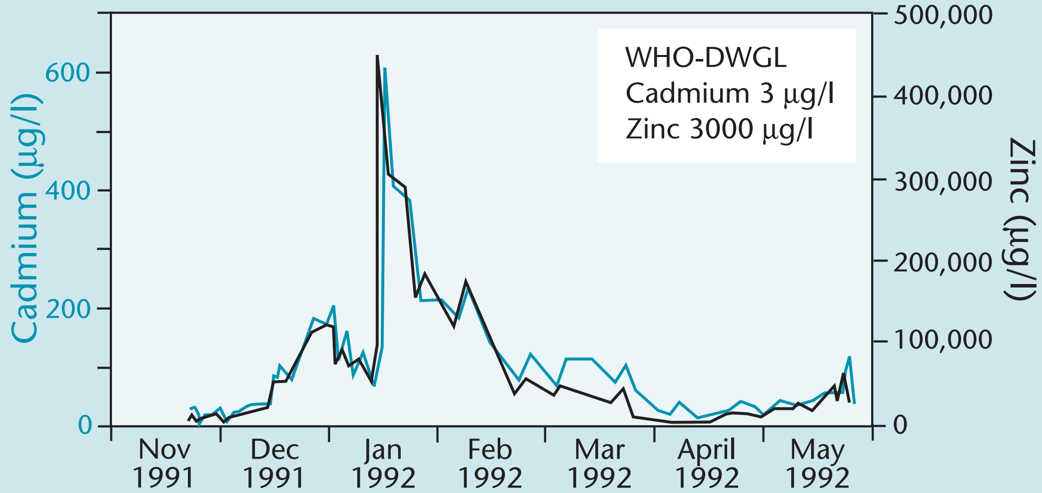



*Figure B. Cadmium and zinc levels in the River Carnon November 1991-May 1992 (from NRA, 1994).*

Although local environmental quality standards of 1µg/l for cadmium and 500 µg/l for zinc had been exceeded by factors of several hundred times, the effect on the river was muted as aquatic life was not generally abundant. This was because the localised mining activity had been causing the river to fail its quality criteria for many years. No private water supplies were in the immediate area of the discharge either. Low cost passive treatment was later installed, comprising flow control with tertiary treatment to reduce acidity and achieve controlled deposition of metals.

**BOX 35 CONTAMINATION OF POTABLE GROUNDWATER SUPPLIES BY TIN MINING; RON PHIBUN, THAILAND**

Ron Phibun in southern Thailand lies at the foot of mountains east of a heavily cultivated alluvial plain that extends to the Gulf of Thailand. Potable water supply is generally obtained from shallow wells sunk in the alluvium. Ron Phibun is a tin mining area, and the common occurrence of the sulphide mineral arsenopyrite (FeAsS) associated with the tin ore means that arsenic is also present in mine wastes.

One survey in the late 1980s identified over 800 cases of chronic arsenic poisoning and another amongst 131 school children showed 44 per cent had high levels in hair and 78 per cent high levels in fingernails in the sample. Further work indicated a statistically significant relationship between children's reduced IQ and hair arsenic levels.

A number of mine wastes types have been identified as possible sources of arsenic contamination of the water supply. They include:

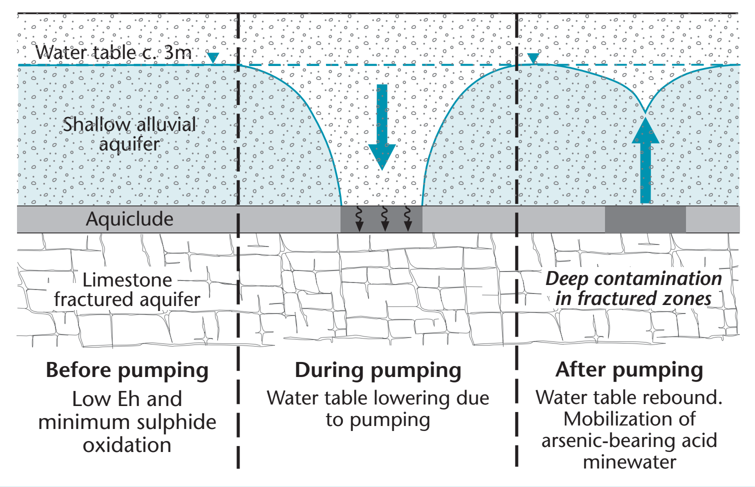
- Arsenopyrite waste in bedrock mining localities in the mountains;
- Sulphide rich wastes at treatment plants and small scale prospecting operations;
- Alluvial tin workings.

The release mechanism from mine wastes is by a weathering process of the sulphide wastes similar to that generating acid mine drainage (AMD):

$$4\ FeAsS + 13\ O_2 + 6\ H_2O = 4\ Fe^{2+} + 4\ AsO_4^{3-} + 4\ SO_4^{2-} + 12\ H^+$$

Investigations concluded that the main source of contamination was from areas of illegal mining in the mountains. An environmental survey of water sources revealed that the most affected villages were clustered in the alluvial tin mining area and that more than two thirds of the drinking water supplies were contaminated, with about 3 per cent of these exceeding the then WHO guideline level of 50 µg/l As*.

The likely principal cause of the arsenic contamination is arsenopyrite oxidation caused by dewatering during alluvial mining activities followed by dissolution of the oxide arsenolite precipitated by post mining groundwater rebound (see Figure).




*Conceptual model of arsenic contamination of Ron Phibun aquifer by alluvial tin mining activities.*

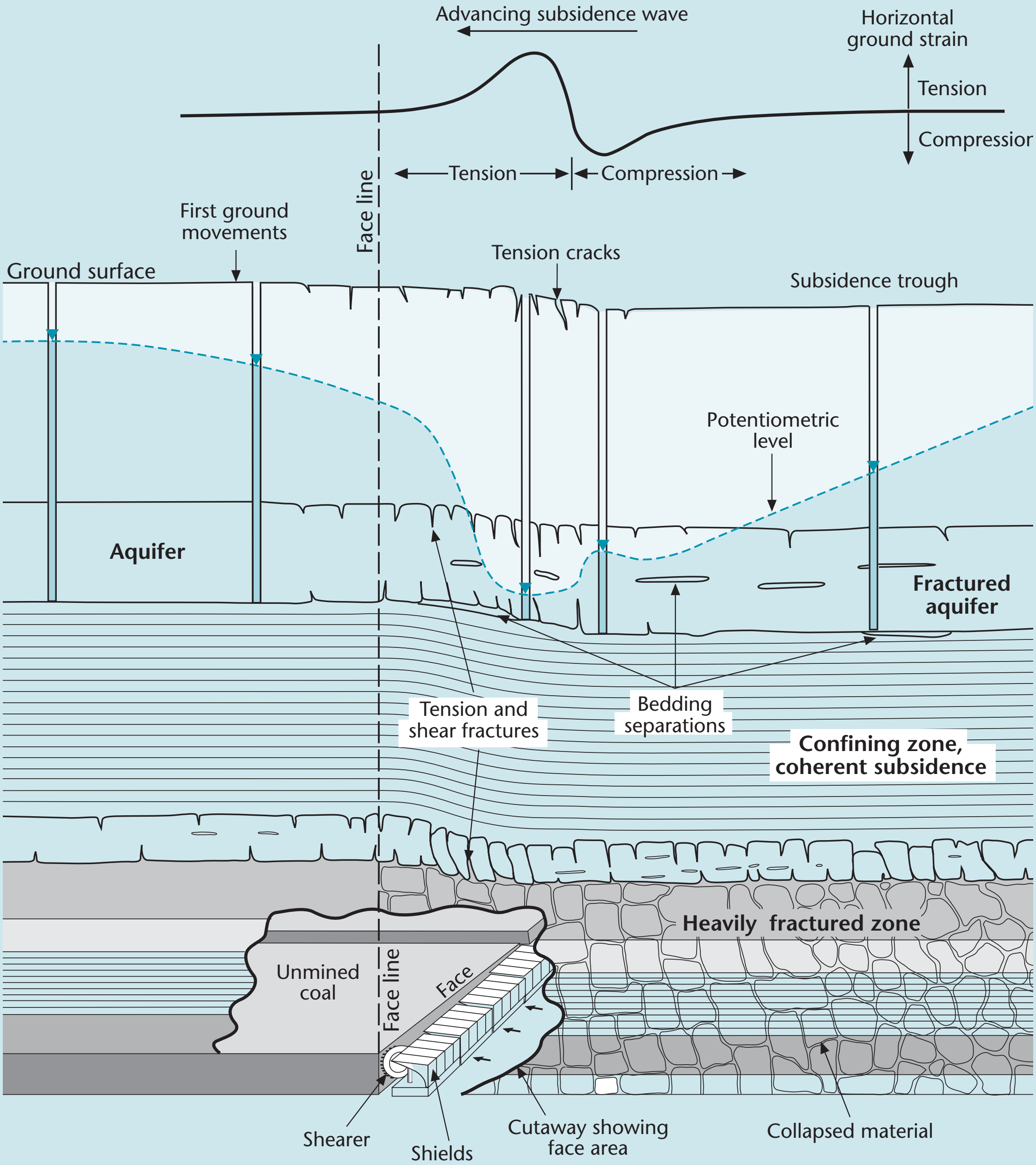
This conclusion has major implications for future remediation strategies. The Thai government has already cleaned up 3000 tonnes of high-grade mine waste and there is concern whether this was a suitable risk management strategy. A long-term study is required to further understand the incidence of arsenic-induced illness. More involvement of the exposed villagers is also paramount if risk management strategies based on groundwater substitution by rainwater harvesting are to succeed.

* *subsequently revised down to the present WHO-DWGL of 10µg/l As*

**BOX 36 EXAMPLE OF EFFECTS OF COAL MINING ON AQUIFER PROPERTIES: SELBY COALFIELD, ENGLAND**

In the Selby coalfield in eastern England, a 2.5 m thick seam is mined by longwall extraction at depths of 550 to 600 m in a formation underlying a regionally important Permo-Triassic sandstone aquifer heavily used for public and private water supply. In a study, water levels were constantly monitored for a two-year period in observation boreholes overlying or close to two longwall panels being mined in the underlying coal measures. Regular cyclic abstraction from a nearby factory allowed pumping test analysis to be used to calculate the transmissivity of the sandstone aquifer before, during and after undermining.

Pre-mining mean transmissivity values for one observation well were in the range 186 to 231 m2/day and increased by nearly 2000 per cent during underworking or close approach by the longwall panels. After working of both panels had been completed, post-mining transmissivity values remained higher than the original values at 257 to 540 m2/day (increases of 138 to 234 per cent).




*Conceptual model of typical water level response in aquifer overlying longwall mining operation (after Booth, 2002).*

# 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

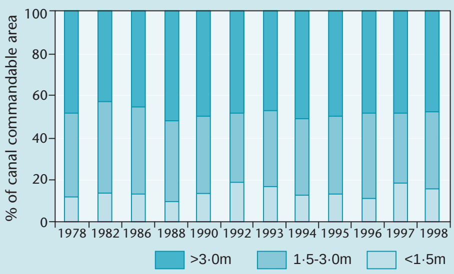
The Lower Indus Valley, shared between Pakistan and India, contains the largest contiguous irrigation system in the world, and was gradually developed over a period of some 60 to 70 years to the middle of the 20th century. The system eventually comprised 3 major reservoirs, 21 barrages or major headworks 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.

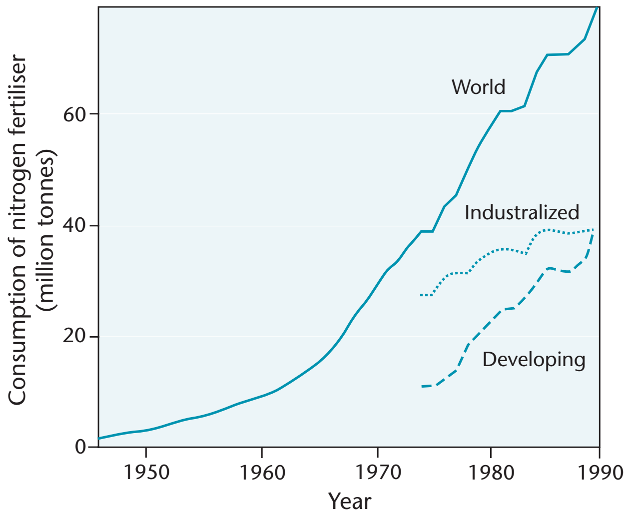



*Figure 21. Consumption of nitrogen fertiliser, 1946-1989.*

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).

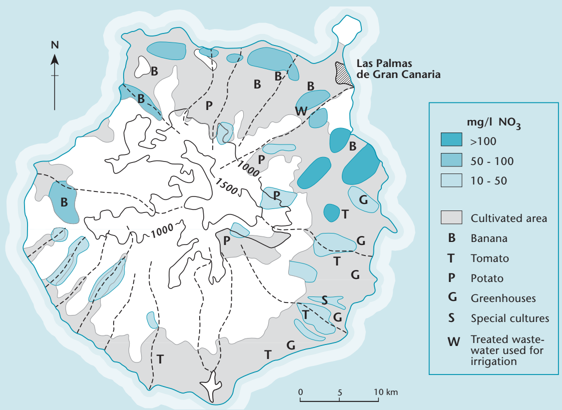



*Figure A. Distribution of groundwater nitrate on Gran Canaria Island (after Custodio et al., 1984).*

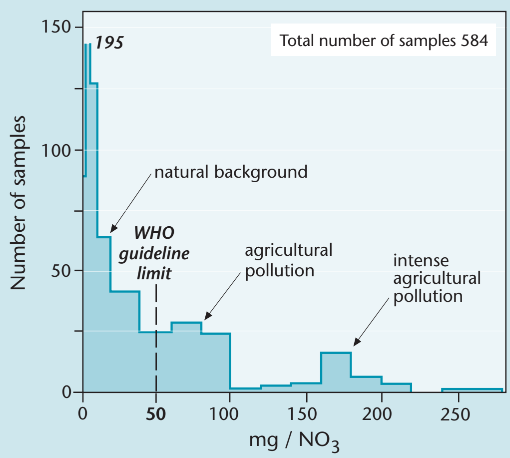
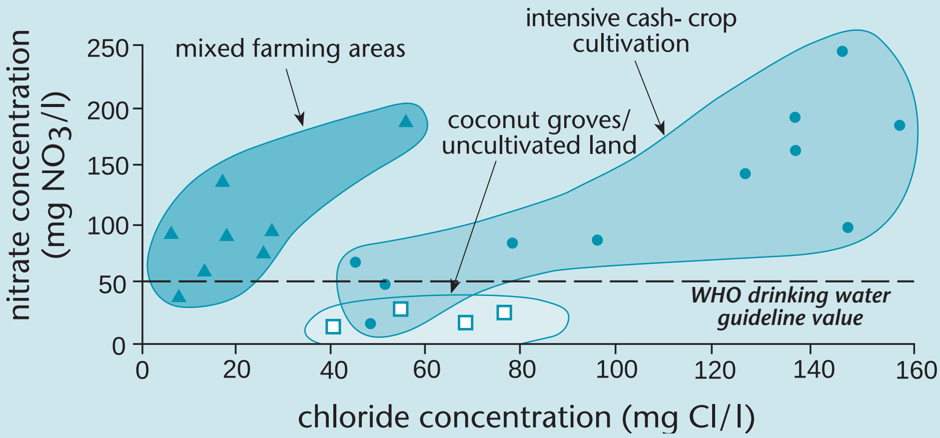



*Figure B. Distribution of nitrate concentration of samples from deep large diameter dug wells on Gran Canaria Island (after Custodio et al., 1984).*

## 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).

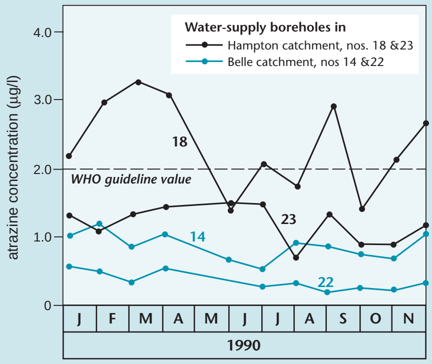



*Figure A Groundwater atrazine concentrations in Barbados catchments under sugercane cultivation (from Wood and Chilton, 1995)*

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.

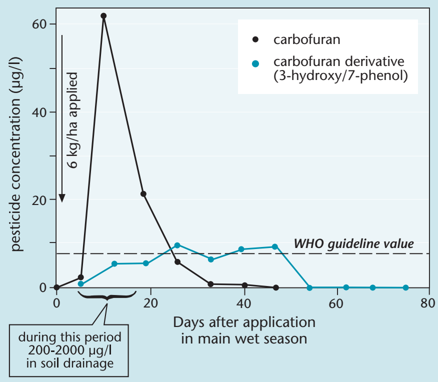



*Figure B Leaching of the insecticide carbofuran from irrigated horticulture to shallow groundwater, Kalpitiya Peninsula, Sri Lanks (from Mubarak et al., 1992)*

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

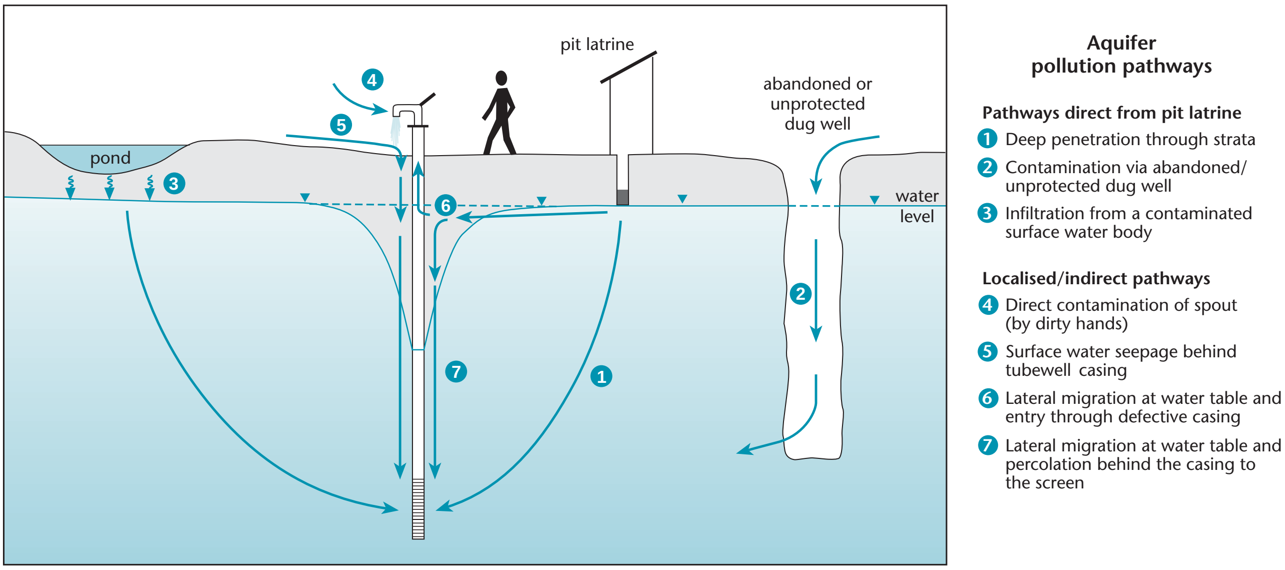



*Figure 22. Pathways for pollution of groundwater supplies by on-site sanitation.*

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<br>no cracks in apron<br>no ponding of water on the apron<br>the join between apron and the casing/lining is sound<br>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<br>fencing excludes animals from the well head<br>diversion ditches direct run-off away from the well head<br>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<br>retaining wall and other protection works kept in good order<br>fencing excludes animals from the backfill area |
| | Immediate area managed properly | diversion ditches direct run-off away from the backfill area<br>good drainage of waste water from spring<br>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<br>well head raised by at least 0.3 m and covered by slab<br>no cracks in apron<br>no pounding of water on the apron<br>join between apron and the casing/lining is sound<br>floor is sloped away from the well head<br>hand pump or windlass and dedicated bucket used to withdraw water |
| | Immediate area managed properly | fencing excludes animals from the well head<br>diversion ditches direct run-off away from the well head<br>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

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

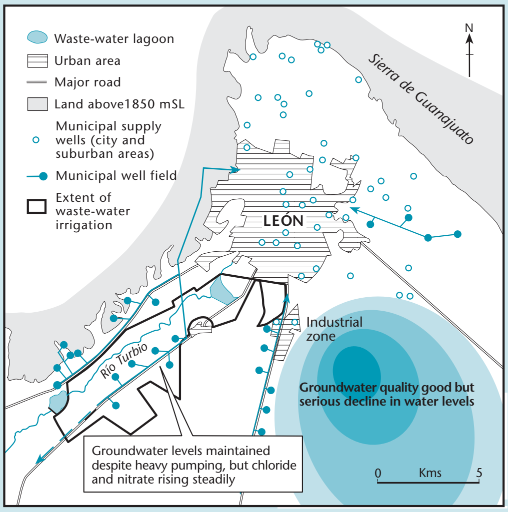
**Table 32 Examples of waste-water irrigation approaches**

| 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.*

# PERSPECTIVES ON GROUNDWATER MANAGEMENT

8

In this section we present two apparently contrasting perspectives on groundwater management for readers to consider. The first is a 'technical' view that proposes a measured approach to management based on the reinforcement of existing institutions to tackle hydrogeological problems in a logical and progressive way. The second view proposes a more holistic approach to sustainability, in which coping strategies as well as technical measures form part of the groundwater problem-solving process. This more iconoclastic perspective is prompted by doubts that the problems associated with groundwater can be solved by existing institutions and management systems.

## THE MEASURED APPROACH TO GROUNDWATER MANAGEMENT

### OVERVIEW OF THREATS AND IMPACTS

It is clear from the preceding chapters that groundwater is a globally important water resource. Its advantages include:

- ability to develop aquifers easily and inexpensively in an incremental fashion;
- generally good quality of water, requiring little additional treatment to make it fit for a particular purpose;
- large storage is available in many aquifer systems, proving a buffer against adverse circumstances, whether climatic (droughts) or induced by human activity (overdraft, pollution events).

However groundwater is under threat from problems that affect both the quantity and the quality of water that aquifers provide.

*Quantity problems* Increase in demand can provoke over-abstraction, which in turn leads to wells drying-up; conflict between users and in some circumstances the incursion of saline water. The drying-up of wells, although serious in the short term for some users, can normally be reversed by reducing abstraction or by measures to increase recharge. In contrast, the incursion of saline water is more problematic and in serious cases could force the effective abandonment of an aquifer for most water users. Nevertheless, even where saline intrusion is not involved, major over-abstraction of a large aquifer can have an enormous momentum, especially if many influential users are involved, for example in the Upper Guadiana Basin (Box 44).

*Quality problems* The problems of pollution from both diffuse and point sources have been described in Chapters 4, 6 and 7. Point sources (from urban, industrial and mining activities) can be locally very serious, but in terms of total aquifer volume are usually small unless they are so closely spaced as to cause widespread pollution (multipoint sources). Diffuse pollution, from agriculture for instance, is normally at lower concentrations but is much more widespread and affects a large volume of the aquifer or a high proportion of its recharge.

Major threats from diffuse pollution or multipoint pollution include:

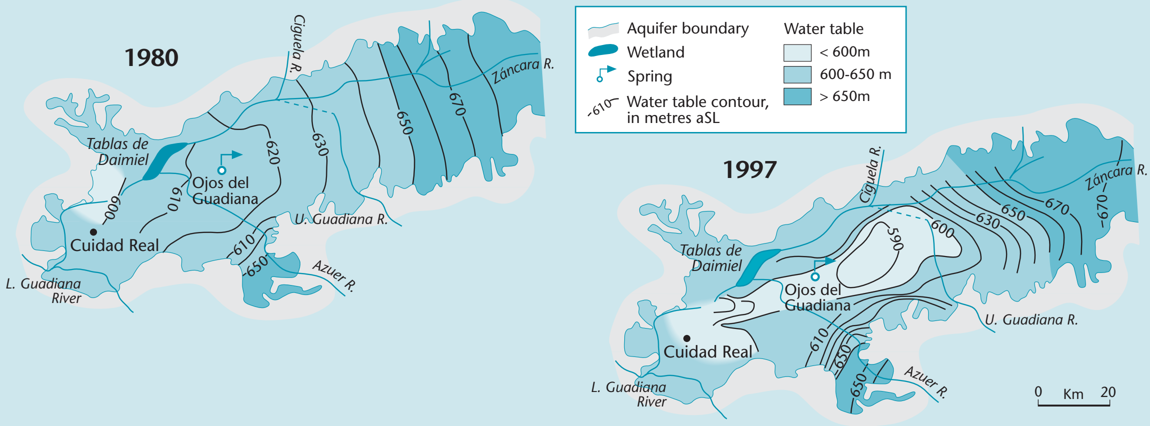
- salinisation, either from over-irrigation and waterlogging or saline intrusion. This is a major problem worldwide and one that has proved difficult to reverse;
- microbial contamination from on-site sanitation or poor well design, construction or siting. The widespread reliance of both rural and urban populations on groundwater for drinking water supply, often with minimal precautionary disinfection procedures means that pathogens entering groundwater-based supplies can potentially cause serious health problems. The poor rate of sanitation coverage worldwide is likely to result in a major increase in on-site sanitation.

The magnitude of these and other threats to the sustainability of a groundwater resource can be quantified by the impact the problem has on society and the environment. For instance in the case of microbial and a number of chemical contaminants, the pollution risk reduces with increased travel time in the subsurface and increased aquifer storage. These factors provide more scope for natural attenuation and for dilution of contaminants to the point at which they would not pose a pollution hazard.

**BOX 44 WETLANDS VS IRRIGATION: GROUNDWATER MANAGEMENT CONFLICTS IN CENTRAL SPAIN**

The Upper Guadiana Basin in the central Spanish Plateau covers an area of 16 000 km$^2$. The climate is typically semi-arid Mediterranean, with average annual rainfall of 450 mm, but marked variability from year to year. Two thirds of the basin is underlain by important and productive limestone aquifers which are connected to the surface water system in complex ways depending on permeability, local topography and groundwater levels. This interaction between flat topography, river system and shallow groundwater produced a variety and richness of wetland ecosystems occupying more than 300 km$^2$.

Development since the 1970s has expanded the irrigated area by increasingly intensive use of groundwater, especially from the Mancha Occidental aquifer in the centre of the basin. Traditional irrigation from wells providing about 60 million m$^3$ annually to 300 km$^2$ was gradually displaced, and by the mid 1980s more than 1250 km$^2$ was under irrigation, using up to 600 million m$^3$/a of groundwater, applied mostly by sprinkler. Groundwater levels declined by as much as 20 to 30 m, and some estimates suggested that the Mancha Occidental contributed a third of the total national annual groundwater deficit. Most of the Tablas de Daimiel wetlands (an internationally important wildlife area) were affected to some extent, and the well known 'Ojos del Guadiana' springs have been dry since 1984.




*Effects of intensive pumping on wetlands of Guadiana Basin, Spain (from Custodio, 2002).*

Because of their overiding ecological importance, UNESCO designated the main wetlands as a Biosphere Reserve and La Mancha Húmeda became known throughout the world. The Spanish government, having previously provided strong incentives for agricultural development in the region, was obliged to take action. However, although Las Tablas de Daimiel had been declared a National Park in 1973, it had almost disappeared as a result of water table depletion.

Attempting to control abstraction and promote crops that would require less water was only partially successful, and the government enacted emergency legislation to import water from the Tagus basin via the Giguela River. However, enlarging the channel of the Giguela to carry the imported water damaged the wetlands along its course, endemic species from the Tagus basin were introduced, and the difference in chemical quality of the Tagus water may have adversely affected the ecosystem of the Mancha Húmeda. The consequences are still being debated, but it is clear that Las Tablas de Daimiel are now artificial, and further restoration would be difficult with the groundwater levels remaining at current depths. The difficulty of reconciling the ecological and economic water management objectives of the various stakeholders in the region is illustrated by the fact that up to 9000 new illegal boreholes have been drilled in the Mancha Occidental aquifer since it was declared 'over-exploited' in 1994.

In other cases, the hazard may not be diminished by the natural properties of the subsurface and intervention is vital to reduce risk. Salinisation is a good example, because salinity is not degradable, is mobile and can arise either from human activities (over pumping, over irrigation) or from the natural disposition of saline water and freshwater worldwide.

A further crucial factor controlling the impact of pollution is the water use and whether there are alternative sources for that use. Where use is quality sensitive or where no alternative source of water can be found (or is very expensive) the impact will be greater.

## MANAGEMENT RESPONSES

Effective management requires:

- awareness of the status of groundwater—both its quality and the quantity available. It follows that monitoring is a prerequisite in order to identify whether problems are occurring or are likely to occur;
- understanding of the aquifer sufficient to be able to identify options (and targets) to remedy a problem situation;
- water laws and rights in place, widely accepted and clear, or in their absence a practicable system of incentives/disincentives;
- surveillance, to monitor adherence to regulatory measures or response to incentives/disincentives;
- awareness in governmental planning and society at large of the importance of groundwater.

Unfortunately these requirements are very rarely met in full. In particular, water rights and laws applied to groundwater can be ambiguous or uncertain in their interpretation, especially as customary practice or common law typically vests ownership with landowners despite the nature of groundwater as a common pool resource. This is defined as a natural or man-made resource used simultaneously or sequentially by members of a community or a group of communities, for example rangelands, forests, seasonal ponds, wetlands and aquifers. Even where a regulatory framework exists, enforcement may be politically unacceptable or hindered by a lack of resources. The knowledge gap too should not be underestimated. In some countries there is only limited understanding of aquifer systems and inadequate monitoring to assess the groundwater status; this frustrates attempts to inform planners and legislators.

Thus while recommendations can be made, their implementation can be difficult. Realistically, changing the situation will take time, but long term goals need to include:

- increasing public and government awareness so that legislation on water issues (like ownership and rights) can be passed and enforcement accepted by society at large;
- resourcing agencies to actively manage groundwater. The support of aid agencies and other international development organisations should be welcomed, especially where aid programmes may impact on groundwater use;
- encouragement of community management. There is much potential for small-scale users to recognise their self-interest and manage groundwater for their collective good. There will be a commensurate need for informed technical advice on the aquifer system and on the definition of targets for water levels, abstraction and use;
- 'light management' options. Incentives (or disincentives) to reduce pollution load or abstraction are introduced and the agency is involved only in recommending targets and monitoring to see if the measures are working, not in enforcing or promulgating legislation.

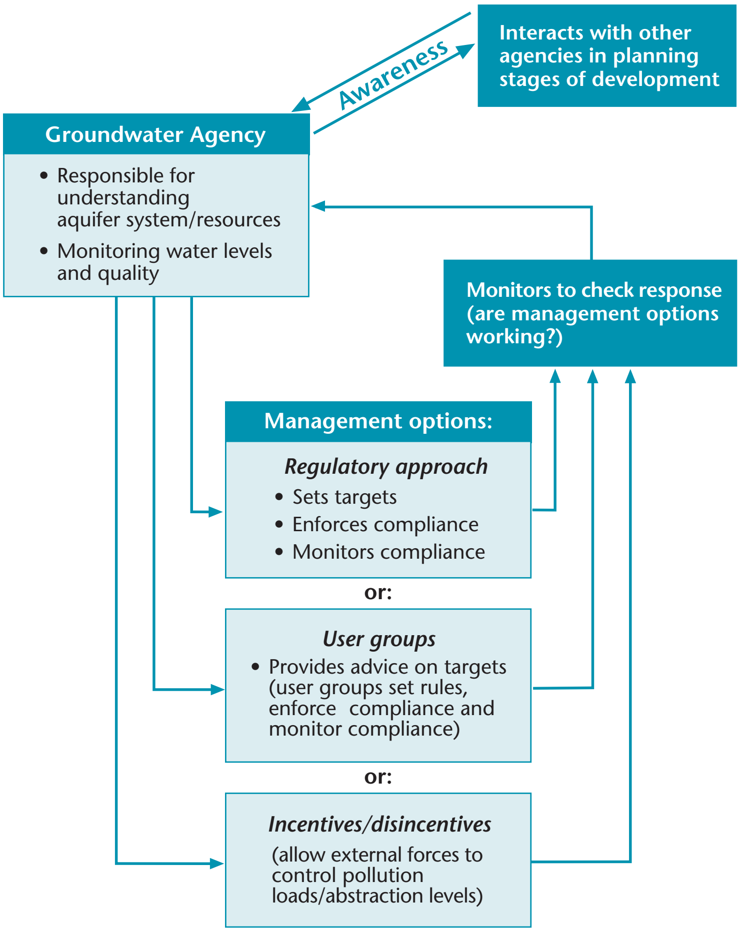



*Figure 23. Range of responses that might be adopted by a groundwater agency when dealing with a groundwater problem; including 'light' management options.*

**Table 33 Example of groundwater action checklist for problems affecting groundwater resources of a region**

| District | Type of groundwater problem | Effects so far | Likely impact if no action | Proposed action | Performance measure for current 4-year period |
|---|---|---|---|---|---|
| District A: extensively irrigated by both surface water and groundwater | Water-logging and salinisation | * ha seriously affected by salinisation<br><br>* ha moderately or seriously affected by water logging and rising soil salinity | * ha abandoned for all crop production<br><br>* ha abandoned<br><br>Complete loss of horticulture industry | Install and operate monitoring network to assess extent of problem<br><br>Assess current irrigation practice<br><br>Assess optimum solution to halt trend in waterlogging using field studies or pilot projects to gauge best choice | Publish audited annual statistical digest<br><br>Year 1 survey of Zone Y<br><br>Year 2 survey of Zone Z<br><br>Year 3 Summary of practice, recommendations for improvement<br><br>Year 4 Set up pilot control area |
| District B: fast - urbanising coastal province | Saline intrusion | Industrial boreholes with electrical conductivity 1000 mg/l<br><br>†public supply boreholes with chloride content >250 mg/l | Forced relocation of food processing and beverage industry<br><br>Cuts in service and increased public water supply costs while alternative distant supply developed | Set targets for quantity abstracted or water level<br><br>Install and operate monitoring network to assess effectiveness of measures<br><br>Inform all stakeholders of likely consequences of inaction | Publish mean annual chloride content in indicator wells<br><br>Publish water levels in key monitoring wells |
| District C: upland livestock farming area | Microbial contamination of rural (farm and village) well water supplies | Gastro-intestinal disease morbidity statistics‡ % higher percentage than comparable provinces | Continuing abnormally high rates of infant mortality and community gastro-intestinal disease prevalence rates | Rural well sanitary survey<br><br>Good practice publicity campaign for community well users<br><br>Issue operators with a well construction and design guide<br><br>License and inspect well construction enterprises | Complete survey by Year 1<br><br>Inaugurate campaign on all media from Year 2<br><br>Issue guide Year 2<br><br>Set up licensing and inspection Year 4 |
| District D: urban, industrial and transport hub | Aquifer contamincated by industrial products<br><br>General decline in urban well water quality | †wells contaminated by chlorinated solvents<br><br>†wells contaminated by petroleum products<br><br>†wells with rising $NO_3$ content | Likely loss of† public supply wells in industrial and commercial zone<br><br>Steep increase in public water supply costs if main well field starts to exceed WHO/national quality limits | Install and operate monitoring network to assess extent of problem<br><br>Assess aquifer vulnerability and contaminant load<br><br>Make inventory of activities in public supply well field catchment<br><br>Press for regulatory control | Publish audited annual statistical digest<br><br>Conduct reconnaissance survey by Year 3<br><br>Create inventory by Year 3<br><br>Identify and prioritise main threats by Year 4 |

** User to insert estimated area affected*
*† User to insert number*
*‡ User to insert percentage*

Table 33 provides a simple example for a fictional but realistic regional groundwater situation and is presented as a guide or a concise action checklist that government, political representatives, the public and the media alike can refer to when discussing a country's groundwater issues. Figure 23 shows the different management options that a groundwater agency could use to help government/users resolve groundwater quality or quantity problems.

## COPING STRATEGIES AND INDIRECT WAYS OF MANAGING GROUNDWATER RESOURCE

**BOX 45 REALPOLITIK**

The mark of effective research, advice and policy-making is the capacity of those involved to 'know the difference' between what **should** be done, and what **can** be done (Allan, 2001).

The innovator makes enemies of all those who prospered under the old order, and only lukewarm support is forthcoming from those who would prosper under the new. (Machiavelli, 1513).

### WHAT SHOULD BE DONE? THE CONVENTIONAL APPROACH

Water resource professionals often have a vision of what an ideally managed water resource system should look like, based on the principles of welfare economics and integrated water resources management (IWRM). This vision has an intuitive and intellectual appeal that is not easily contradicted. The basic principles are well rehearsed and include, for example:

- water should be treated as both an economic and a social resource, and priced accordingly;
- that 'rights' should be specified and enforced according to social, economic and environmental priorities (often in this order);
- the concept that the 'polluter pays';
- surface and groundwater flows and the services they provide should be considered in an integrated and holistic way.

Groundwater has been notable by its absence in the debate on IWRM, or it has been added to policy statements almost as an afterthought. This situation is changing, albeit slowly. Management prescriptions now offered are based on the same set of basic principles, but are typically elaborated with the following types of recommendation:

- public ownership of groundwater needs to be legislated, with the state or government granting rights of use;
- an allocation/licensing system needs to be developed, based on sustainable yield assessments, with priority given to domestic use;
- groundwater pricing needs to be introduced, based on the principle that water is an economic as well as a social good. Users need to be confronted with at least part of the full economic cost of groundwater, including marginal costs;
- a groundwater pollution strategy needs to be developed and implemented, including land use zoning and application of 'the polluter pays' principle;
- the environmental services provided by groundwater, including base flows to rivers and wetlands, ought to be recognised and protected within an 'integrated' planning framework.

It is the contrast between this vision of what **should** be done, and the reality of what **can** be done in most developing countries, that is so striking. In particular, the apparent importance of, and acceptance given to, such recommendations have obscured the assumptions on which they are based, and their very limited application in the real world.

In this section of the report, we argue that 'conventional' approaches to groundwater management of the large aquifers that are at risk in many developing countries must be reassessed. This is because management of the type envisaged by these conventional approaches presupposes the existence of institutional, legal and technical preliminaries that are simply not in place. In particular, effective strategies are constrained by:

- a chronic lack of data on groundwater conditions and trends. This has resulted, in part, from the 'out of sight, out of mind' characteristics of groundwater. It is persistently undervalued, and there is always a time lag between the cause of the problem (for example over-abstraction and pollution) and its effect (for example falling water levels or quality deterioration);

- the large numbers of individual users typically involved in pumping and polluting activities at the aquifer scale. The coordination or control of these activities is a formidable challenge, even with reliable and comprehensive data on aquifer conditions and usage;

- the intensely private nature of much groundwater development. Irrespective of the views of state or government on ownership and rights of use (which are often ambiguous), customary rights to groundwater are often deeply entrenched. Changing these perceptions, and the belief systems that underpin them, is a long and highly contested process. There is no reliable checklist nor handy tool kit with which to change the perceptions of large groups of people quickly. In the Murray Darling Basin in Australia, for example, it has taken about 10 years to get water rights defined. This in a country with literate farmers, a respected and transparent legal framework and other critical characteristics;

- the limited institutional capacity of fledgling management organisations. Many of the bureaucracies now tasked with management are poorly equipped to deal with new economic and regulatory approaches to managing demand.

Drawing on the last three points, in particular, a key contention of this section of the report is that ‘conventional’ management approaches are constrained by a lack of social and political support for difficult economic and regulatory reforms, and by major institutional bottlenecks. Nonetheless, there remains an army of sector professionals who are convinced that regulatory and economic instruments can be implemented because they make sense. There is a failure to realise that their financial and legal solutions present huge political and institutional problems for those charged with implementing them.

## WHAT CAN BE DONE? UNDERSTANDING SOCIAL AND POLITICAL FEASIBILITY

This section draws heavily on continuing work in the Middle East and South Asia by BGS publication team member Roger Calow and by experts on Middle East and North Africa water policy such as J A Allan, Kings College, London (see Bibliography list).

**Sustainability and the central role of politics**

Sustainability, in the context of the social and political feasibility of reform has three essential dimensions (Figure 24). Environmental sustainability is interpreted here as the sustainability of groundwater volume and quality. It must be analysed in conjunction with simultaneous evaluations of the sustainability of the economic and social contexts in which the environment is viewed.

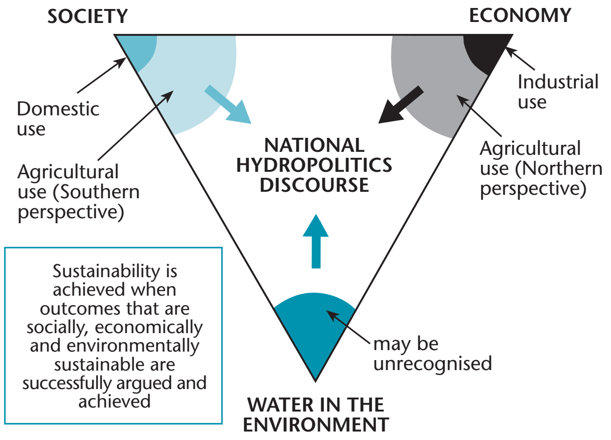



*Figure 24. Different dimensions of sustainability when considering social and political feasibility of water reform (from Allan, 2001).*

Clearly the three dimensions of sustainability are related, but the achievement of long term economic and social sustainability that is the ultimate objective of development does not imply that groundwater resource conditions must be maintained in a particular state. Rather, it implies accumulation, in the broadest sense, of ‘capital’ that provides the basis for improved livelihoods, especially for poor people (DFID, 2000). Substitution between different types of capital is possible, and may be both economically and politically rational. For example, tensions and trade-offs may occur between:

- locally identified needs for greater livelihood security, and wider concerns about environmental sustainability. In many Middle Eastern and North African (MENA) countries for example, agriculture is, and will continue to be, the major user of groundwater, despite wider concerns about its environmental (and economic) rationality;

- the maintenance of production or income during droughts, and concerns about the impact of groundwater mining (of uncertain length) on regional aquifers. These concerns come regularly to the fore in Israel, for example.

Figure 24 also illustrates how each of the three dimensions of sustainability has a voice in the politics of a country. Understanding the strength of the respective voices, and why they are present or absent, is vital. This requires analysis of the mediating politics, as this determines which knowledge, or view, is given attention, and which is assimilated by firstly those making water policy, and secondly by those using and allocating water. Scientific knowledge on water is important, but it does not generally determine water policy: political necessities are usually more compelling.

It is also important to appreciate the different views on groundwater management and the allocation of priorities. Figure 24 illustrates how, in many southern countries, water is perceived as a social resource. In rural communities, for example, water for agriculture has been viewed as an entitlement legitimised by religion, social convention, and long-standing customary practice. The voice—and political power—of agricultural users and lobbies is therefore very strong. In India for instance, agricultural interests have been able to frustrate reforms on power pricing and groundwater regulation that are economically and environmentally 'rational'.

Those pushing for reform—especially donor agencies—view water as an economic resource, and emphasise the need for demand management, including the reallocation of water to sectors offering higher returns. Such messages, however, and the economic and regulatory innovations involved, are not rooted in engineering science or easily assimilated by the bureaucracies which have allocated and managed water for many decades. Neither are they rooted in communities that have, for many years, considered water as a free entitlement.

**The political feasibility of reform**

As noted earlier, water policy is the outcome of a contentious debate between different stakeholders, with varying interests and perspectives. As an example, Figure 25 is drawn from an analysis of water

**Economically and environmentally logical policy priorities**

**1. Achieve strategic water security**

Secure supplies of **'virtual water'** by **regional cooperation** in the international food trade

**2 & 3 Achieve improved water use efficiency**

**2.** Apply principles of **demand management** to improve **efficiency in allocation** and **returns to water:**
- farm level - raising water efficient crops
- inter-sectoral re-allocation
- international re-allocation

**3.** Implementing measures of **productive efficiency** to improve **returns to water:**
- farm level - improving water distribution, drainage, technologies
- irrigation - as for farm but emphasing institutions, pricing etc
- urban waste water reuse

**Comments**

The idea of **food insecurity** is sensitive in most Middle East countries and therefore the relationship between water and food deficits cannot be debated.

Middle East governments and officials welcome policies promoting **improved water use efficiency** by investment in technologies, civil works and institutions

Policies promoting **measures to improve more efficient allocation of water**, are unacceptable to Middle Eastern governments and officials because they are politically stressful

**Politically feasible policy priorities**

**1 & 2 Achieve improved water use efficiency**

**1.** Implementing measures of **productive efficiency** to improve **returns to water:**
- farm level - improving water distribution, drainage, technologies
- irrigation - as for farm but emphasing institutions, pricing etc
- urban waste water reuse

**2.** Apply principles of **demand management** to improve **efficiency in allocation** and **returns of water:**
- farm level - raising water efficient crops
- inter-sectoral re-allocation
- international re-allocation

**3. Achieve strategic water security**

Secure supplies of **'virtual water'** by **regional cooperation** in the international food trade

**Notes**

These water policies would provide remedies to ameliorate the water predicament of Middle Eastern and North Afican (MENA) economies. However the analysis shows that economically and environmentally urgent policies are not a 'politically logical' way to approach the amelioration of the region's water problems. Measures to stimulate waste water reuse are 'politically logical' and certainly more 'politically feasible'.

*Figure 25. Contrasting views on the prioritisation of water management policies in Middle Eastern and North African countries (Allan, in Calow et al., 2001).*

management policy in the Middle East and North Africa, and highlights the contrast between 'outsider' (for example donor agency) professional analysis of water policy options, and that of 'insider' water users and policy makers (for example irrigators, government). Within this scheme, the term 'Virtual water' is used. This was originally applied to the valuing of imports in an economy and describes the water that would otherwise be required by a country to produce the commodities it imports. For example, a tonne of grain typically requires 1000 tonnes ($m^3$) of water to produce it.

For those donor agencies or outsiders who advocate new principle-based reforms aimed at increasing overall economic returns to water, the import of 'virtual water' and reallocation of water (from agriculture to other sectors) are the main priorities. They are economically rational. Measures to increase the technical efficiency of water use are given a lower priority as they offer much lower returns in terms of income and employment. In contrast, 'insider' water users and policy makers tend to prioritise in the reverse order. Ways to increase the technical or productive efficiency of water use *within* sectors are prioritised because they are politically benign and carry lower political prices. Hence efforts to increase irrigation efficiency are promoted, as are efforts to increase recharge to groundwater (for example both are advocated in India as a 'solution' to groundwater overdraft). By contrast, reallocation is strongly resisted, as it may involve confronting existing users with sharp political measures. The notion of 'virtual water' is seldom discussed at the political level (South Africa is one exception) as it raises difficult foreign policy questions about the resource insecurity of the country's economy.

The process of introducing and implementing any new policy on groundwater *management* is political. Unwilling governments and water users cannot achieve new economic and legal reforms. Communities and politicians need to know about, and want, innovations in order to accept them for operation. Gaining acceptance of new water regulations requires substantial political investment on the part of the body charged with installing and gaining compliance, and is much easier to achieve once an economy has broadened its economic and social base.

**Strong economies have diverse options**

Water policy options are proportional to the status of the economy. A strong and diverse economy has options which a poor economy that is substantially dependent on agriculture cannot mobilise. These include:

- the ability to control sectoral allocations through different instruments (tariffs, licences, quotas, etc) and mediate between competing claims (especially agricultural and urban users);

- the ability to access water in a range of different forms. For example, while water for domestic and industrial needs must always be found locally, food that can be bought in the market place requires no further water to produce it. Markets may be local, national or international. All of the countries of the Middle East, with the exception of Turkey, compensate for national water deficits by importing 'virtual water', embedded in food, in this way. The Gulf States provide another example, where oil also provides the money needed to desalinate water for domestic needs.

As an economy grows, government and civil society perspectives on water can also evolve. More specifically:

- greater economic diversity enables civil society to widen the range of livelihoods away from water-intensive agriculture. For example, by the time Israel cut its water allocation to agriculture in the late 1980s, there had already been a major shift in jobs to other sectors. Moreover, the proportion of gross domestic product (GDP) generated by the agricultural sector had declined to around 3 per cent and the other 97 per cent of GDP was coming from the 5 per cent of water allocated to industry and services (Box 46);

- those in government can escape from the traditional view that links water, irrigation and economic growth together;

- the voice of urban and industrial users gains in strength as their economic and social importance grows;

- NGOs may also gain in strength, and in their capacity to mobilise opinion within civil society, to lobby the private sector, and to influence water policy.

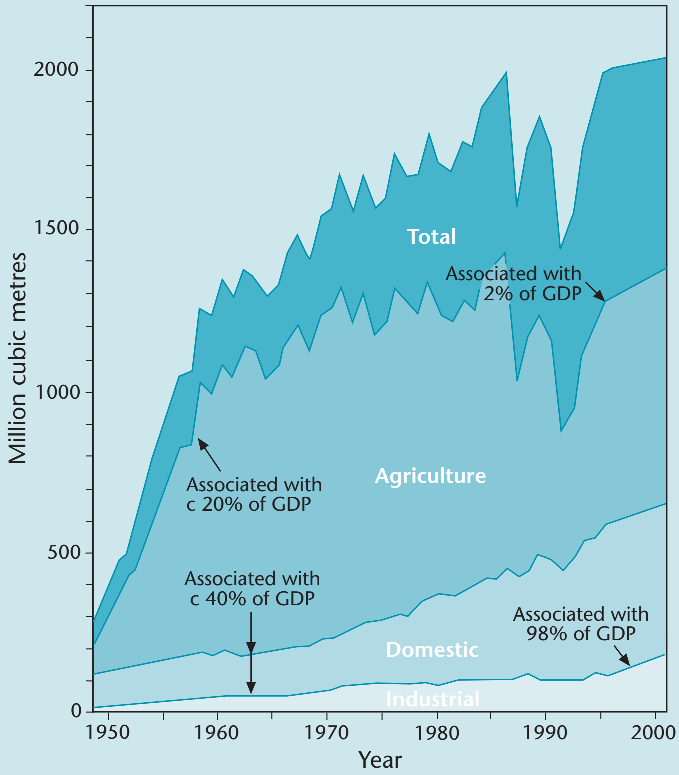
The ability of an economy to deal with water scarcity by achieving economic diversity and strength has been termed the building of 'social adaptive capacity,

## BOX 46 STRONG ECONOMIES HAVE DIVERSE OPTIONS: THE CASE OF ISRAEL (FROM ALLAN J A IN CALOW ET AL., 2001.)

The experience of the Israeli economy since the 1950s demonstrates how an industrialising and diversifying economy in circumstances of severe water resource deficit has the option to change water allocation and management policies. From the 1950s until 1986 Israel deployed policies associated with the idea that water, like other natural resources, could be controlled, and increase in supply could be engineered to meet demand. In the late 1980s, in a major policy shift, Israel reduced its water allocation to agriculture as part of new thinking, which held that water should be valued as a resource that contributed to social and environmental well-being. In other words, water should not be used in the economy at the expense of its capacity to support a sustainable environment and viable society.

The change in water allocation policy in Israel was possible partly because of its industrialised economy. By the mid-1980s, 97 per cent of its gross national product (GDP) came from about five per cent of national water devoted to industry and services (figure below). The change occurred in 1986 because there had been a decade-long campaign by Israeli environmentalists who argued that the water stored in Lake Tiberias/Kinneret, and especially the groundwater in the Western Aquifer Basin of the West Bank, was being used at unsustainable levels. The drought of the mid-1980s became a media event, providing an opportunity for reform.

A dramatic reversal in water allocation policy occurred in Israel after 1992, with a sharp increase in agricultural allocations. This has to be explained by a different theory, centring on the perception and prioritisation of risk. After 1992, when the peace process intensified and talks began between Jordan and Israel, and soon afterwards between Palestine and Israel in Oslo, different risks became salient. Risks associated with the outcomes of the agreements over water were seen to be more important than both the arguments of the environmentalists and of the economists over the misallocation of water to agriculture. The change of policy was also encouraged by an extreme environmental event. The rains of the 1992–93 season were exceptional, and the decline in water levels of the previous decade in the Western Aquifers was rapidly reversed. The key lesson to be drawn is that the salience of environmental priorities is subordinate to the political process of risk perception: hydrogeological numbers are only one element in the political process of water allocation and management.




*Changing water use allocations in Israel, 1949–2000 (source Israel Bureau of Statistics).*

and that for Israel is described in Box 46. The growth of the Israeli economy and other water-scarce economies, such as South Korea, Taiwan and the Gulf States, demonstrates that the development of a social adaptive capacity is not determined by water availability. The experience of Israel contrasts with that of the neighbouring Gaza Strip. In Gaza, groundwater degradation has reached crisis proportions with saline intrusion, falling water levels and widespread pollution. Although the constraints on the aquifer are well understood, controls on pumping are still minimal. This is because it is politically unfeasible to introduce new reforms, such as abstraction quotas and pricing at a time when livelihoods are still heavily dependent on irrigated agriculture.

## POSSIBLE WAYS FORWARD WITH A BROADER WATER RESOURCE MANAGEMENT PERSPECTIVE

The point of the discussion above is not to suggest that conventional approaches to groundwater management based on economic and legal reforms need to be abandoned. Rather, the argument is that such recommendations need to be implemented over the long term. This is because they wrongly presuppose that a good deal of the institutional, regulatory and social infrastructure needed to implement them is already in place, or can be put in place easily, and that substantial technical information on groundwater conditions and trends is available. They also assume that new ideas about the environmental and economic value of water, learned only recently in northern industrialised economies, are politically and socially neutral, when in fact they require the long-term transformation of beliefs and ideologies. This is frustrating, especially for agency officials, development economists and hydrogeologists in a hurry because of limited funding and career horizons.

Where does this leave us in terms of groundwater management? Firstly, it highlights the need to think much more about what **can** be done in terms of policy innovation, not just about what **should** be done. This requires analysis of the wider social, economic and institutional context of reform that influences political feasibility so strongly. Sector professionals will be ignored if they fail to understand the political processes that determine how water is managed and allocated, and if they do not shape their message accordingly. This also implies more careful timing and sequencing of different reforms.

*What can be done now?* Steps can be taken towards registering well users and developing groundwater information systems.

*What can be done to shift the perceptions of water users in the long-term?* Once new knowledge has been constructed and economic circumstances have changed new systems of water rights can be developed and gain acceptance, with fair water pricing etc).

There are circumstances when government and civil society perspectives on water and on norms of management can change quickly, and though we have argued that this is not usually the case, some examples can be given:

- groundwater development controls were accepted reluctantly in Bangkok metropolitan area in the mid-1980s once the cost and inconvenience of continually falling water levels were felt by thousands of private borehole users. Thus where aquifers are of key strategic importance to a defined group of users sharing similar interests, particularly in terms of high-value domestic and industrial supply, an authority that has the power and the support of the user community can establish effective controls;

- in circumstances where a major event, such as drought, causes a short period of convergence in the ideas held by government officials and ministers, the public and the media. Such 'windows of opportunity' provide an opportunity for policy makers to push through difficult reforms that would not otherwise be accepted. The Israeli example in Box 46 is illuminating; the droughts of 1986 and 1991-92 were not *by themselves* sufficient to bring about a change in water policy. However, they succeeded in focussing public attention on the issue of the sustainable use of national water resources.

Where conventional water resource management approaches do not appear viable, more indirect remedies need to be tried. For instance, instead of trying to manage the water resource itself to support water-intensive livelihoods, less water-dependent livelihoods can be supported directly. Livelihood diversification is important because:

- non-food producing livelihoods are much less dependent on local water, and enable food (and thus the water needed to grow it) to be purchased from other regions with more water in markets that may be local, national or international. The key point is that water security depends partly on the ability to access local freshwater (for uses that cannot be substituted, like potable supply) and partly on the ability to purchase water-intensive commodities such as food;

- it helps create the political space needed to introduce water-conserving and reallocating policies over the longer term as civil society becomes differently employed;

- policies that build from existing social trends and activities are much more likely to be supported. In many cases, people are *already* responding to emerging groundwater problems through a variety of coping strategies, or are shifting to non-agricultural activities independently because of the higher (and more secure) incomes on offer. These 'push' and 'pull' factors drawing people into the rural non-farm economy, for example, can be seen in many rural areas of India and China where household incomes are increasingly drawn from non-agricultural sources such as textiles, quarrying or brickmaking.

Policies that could build off existing social trends, or help promote them, are many and varied, but a key criterion is to employ interventions that enable the poor, who may be disproportionately affected by groundwater degradation, to overcome entry barriers. Training and credit are obvious interventions, but they also include:

- measures removing general constraints to growth, including investment in transport, communication and education;

- facilitating urban-rural links, including measures to increase the flow of market and price information to rural areas;

- facilitating enterprise growth, including the development of small towns, supporting producer associations for marketing and sourcing, and the extension of business advisory services into rural areas;

- sector-specific interventions, such as support for industrial clusters and incentives for industrial relocation.

Such interventions fall outside traditional sector boundaries, and suggest a need for water agencies (departments, ministries) to forge unfamiliar alliances, for example with departments of industry, commerce and infrastructure. Nevertheless such approaches—adopted as interim strategies or as alternatives to conventional management—may offer the only viable way of mitigating the impact of groundwater degradation on communities, and of relieving pressure on the resource base.

## MONITORING CONSIDERATIONS

Previous references in this publication to the need for monitoring only serve to underline the fact that monitoring of water quality and water levels in an aquifer is the foundation on which groundwater resource management is based. It provides the information that permits rational management decisions on all kinds of water resource and sustainability issues:

- understanding the flow system and the baseline water quality before development changes both;

- identifying actual and emerging problems of local overdraft (quantity) or water pollution (quality);

- providing independent information on the rate of use of the resource, especially where the regulatory system is deficient;

- evaluating the effectiveness of management actions, including remedial measures to halt or reverse adverse trends in water quality or quantity.

Nevertheless, despite the obvious benefits of monitoring programmes to government and other institutions responsible for managing water resources, it is common, almost the norm, to find that monitoring programmes are the first functions to be cut back when resources are scarce. At the other end of the spectrum, there are also cases where programmes originally devised for preliminary survey purposes have been continued blindly long past the aquifer resource assessment stage and into the development phase without any revision to reflect emerging conditions and new groundwater priorities. The resultant hard-won data are then unsuitable, or poorly suited, for regulatory or planning use, are not used and progressively become discredited as irrelevant to the management process.

These experiences demonstrate that there are only two really vital monitoring axioms:

## BOX 47 URBAN GROUNDWATER POLLUTION MONITORING AND EARLY WARNING NETWORK: AN INNOVATIVE EXAMPLE FROM WEST AFRICA

Numerous African cities rely on groundwater for potable supply, both from shallow private hand-dug wells and from deeper public water utility boreholes (see Figure 2). The unprecedented population growth in these cities, much of it in large areas of unplanned substandard housing and few services, poses a threat to such supplies. On-site sanitation, lack of organised domestic waste disposal and pollution from urban industry are of special concern. In response, a small but innovative UN international project supported jointly by UNEP and UNESCO started in 2000. Project teams in seven West African countries, drawn principally from universities with some support by national agencies aim to establish an urban groundwater vulnerability network and develop locally appropriate methodologies for optimal monitoring of the pollution of urban aquifers.

The network covers seven West African cities; Abidjan (Côte d'Ivoire), Bamako (Mali), Cotonou (Benin), Dakar (Senegal), Niamey (Niger) and Ougadougou (Burkina Faso) with Keta (Ghana), which joined during 2002. The long-term objectives of the project include:

- assessment of groundwater vulnerability;
- establishment of an early warning network;
- identification of pollution hotspots and major threats to the urban aquifer resource;
- development and dissemination of policy options to mitigate such threats;
- hydrogeological modelling of vulnerability.

Although working during the first two-year phase of the project with very modest budgets of about US$ 20 000 per country per year, the small task force teams in each country made significant progress (see table), successfully completing numerous contributory activities.

**Early warning network project programme (from UNEP 2002)**

| Work undertaken during Year 1 (2001) | Work undertaken during Year 2 (2002) |
|---|---|
| Topographical map digitisation | On-site chemical sampling for conductivity, pH, temperature and water level measurement |
| Photo purchasing, scanning of aerial photos | Bacteriological sampling and analysis |
| Keying in of geological data (fractures, structure) | Maintain databases of site chemistry and bacteriology |
| Preliminary data collection, including climatological data (rainfall) | CD-ROM. Data input standardisation |
| Development of computing and internet system | Setting up web site |
| Collation of existing data and transfer to Excel© tables | Data bases transferred to web site as Excel © tables |
| Establish water level monitoring network of identified areas | Issue of draft early warning bulletin and final report |
| Analyses of data | Training in ARC VIEW at Abidjan |
| Mapping of key pollution sources | Vulnerability maps |
| Production of provisional thematic maps. | Update WWW web site and early warning bulletin |
| | Issue final early warning bulletin, report and web site |

The successful establishment of the information network in such a short time and with such slender resources is clear evidence of the high degree of cooperation between the countries and of the sense of commitment of the individual national project teams, all working on a common agenda towards a common goal in their own national context. The number of groundwater professionals in the member states is not large, and important benefits of the network are:

- mutual support and evolving experience of other teams dealing with urban water management problems in similar West African social and cultural settings but contrasting hydrogeological environments. The network can thus learn collectively from individual team experiences what is practical and attainable rather than 'reinventing the wheel' in each country;
- Providing an opportunity for other African cities to emulate the network's activities by making information available on the web site (http://www.unep.org/water/groundwater/Africa/index.asp). This includes *Country Summaries* and *Early Warning Bulletins* each produced by the national teams;
- Such 'diffusion of innovation' provides ready examples to groundwater professionals in other African states grappling with the challenge of urban groundwater.

A second phase of the project plans to build on the successes achieved and also extend the network to three further Anglophone countries (Ethiopia, Kenya and Zambia) as well as Ghana. Its aims are similar to the first phase and it is anticipated that in the process, awareness of groundwater status at all levels will be raised, institutional capacity enhanced and the findings will form the basis for formulating groundwater use policy to safeguard and sustain the resource.

- any programme needs to be judged in terms of the information it will generate. The data must be truly useful and be tailored to management requirements;

- regular reassessment of aims is the best protection for monitoring programmes, which are often regarded as an optional luxury that is costly, resource-consuming and potentially sensitive in the political arena.

Thus for instance the measurement of water levels is a simple but vital function that can generate enormously useful information on resource trends. Management is not however well served if the network design does not respond to aquifer exploitation tendencies, by measuring water level trend in major well fields for instance, or by not continuing with regional gradient observation wells that have become compromised by new nearby major pumping wells.

Similarly, once the baseline quality of an aquifer is established, there is no particular merit in continued frequent groundwater sampling for analysis of major ions, which typically change only very slowly with time. Rather the evolving pattern of activities at the land surface, on the aquifer outcrop and on the catchments to sensitive abstractions should be regularly assessed and indicators chosen to provide early warning of potential problems. It is a poor justification of laboratory resources to continue with an analytical suite just because particular parameters are easy to sample and the laboratory is already set up to determine them routinely.

A significant advantage of such regular reassessment of monitoring objectives is not only that it helps ensure that programmes provide the kind of up-to-date and focused information that those managing water resources need, but also can keep the costs of surveillance down to acceptable levels. A responsive monitoring strategy does not need to be a major drain on hard-pressed national budgets (Box 47) and can provide information for management out of all proportion to the costs of collection and interpretation.

Sometimes the organisation of monitoring and how it can be conducted when available resources are very

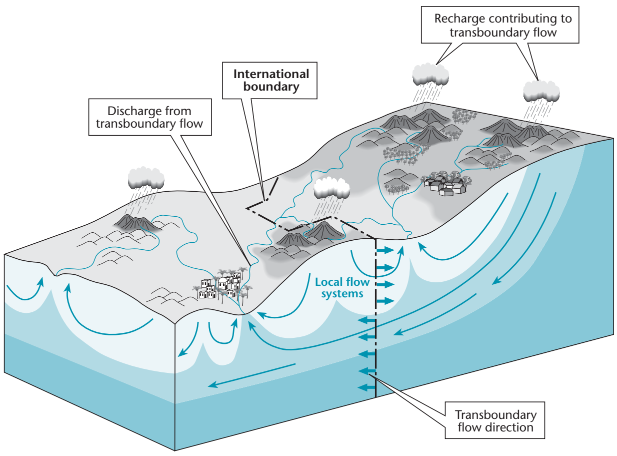
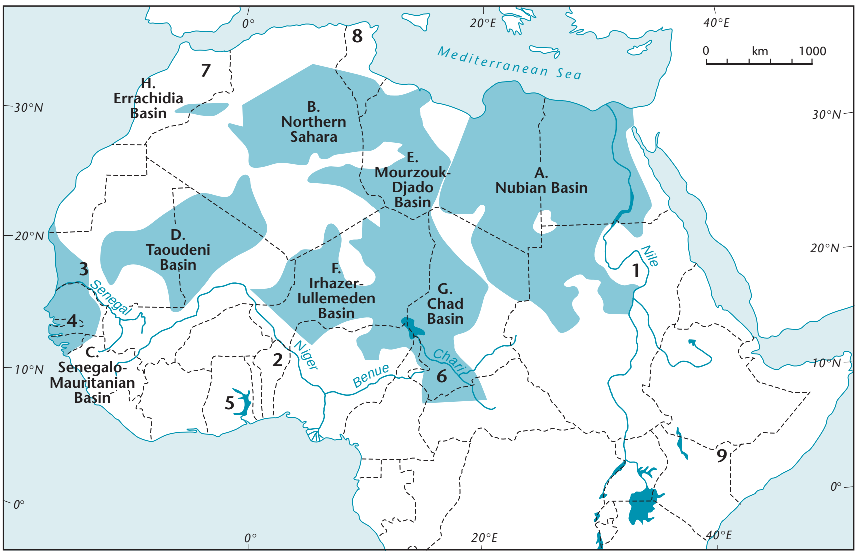



*Figure 26. Schematic illustration of an aquifer which crosses an international boundary (from Puri et al., 2001).*




River basins that cross national borders: **1.** The Nile **2.** Niger **3.** Senegal **4.** The Gambia **5.** Volta **6.** Chari **7.** Guir-Saoura **8.** Mejerdah **9.** Juba-Shebelle

A. aquifers that cross national borders

*Figure 27. Northern Africa: an important region of internationally shared aquifers (from Puri et al., 2001).*

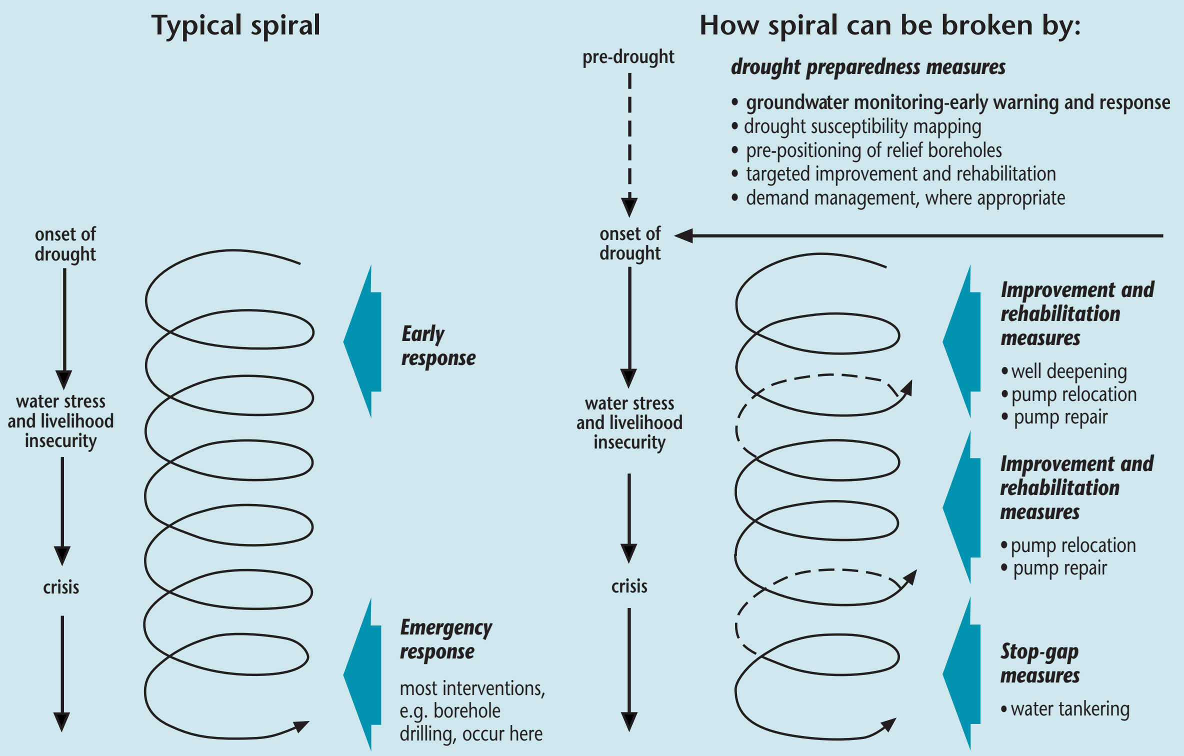
## BOX 48 DATA COLLECTION TO HELP PROTECT THE POOREST COMMUNITIES: AN AFRICAN PERSPECTIVE

In Africa, since the 1980s, there has been a huge increase in the number and quality of disaster early-warning information systems, for example for the onset of drought. Although these systems have become more sophisticated, using both demand side and supply side variables, they are still narrowly food-focused. By to including some simple indicators of water security in the local assessments that are already being undertaken by the many non-governmental organisations (NGOs) and ministries involved in poverty alleviation, a clearer picture of livelihood security and of the interventions needed to support it could be gained at little extra cost. These indicators would include:

- availability, measured by well/spring yield, with indication of why the individual well ‘failed’;
- quality, using a small number of chemical/microbial parameters;
- access constraints (time and labour availability, financial cost, transport).

This information would allow more flexible responses to be made when disaster seems imminent. For example, in protecting the livelihood assets of households in the early stages of drought or rebuilding them in the aftermath of a bad year, a key constraint may be access to water. Thus making more labour available, by protecting livestock or maintaining garden irrigation, could protect livelihoods. Timely water supply interventions may be needed to maintain the water supply, such as repairing the water point, deepening wells or helping with water transport. Water supply activities should be coordinated with food related activities and the rebuilding of other assets, rather than just food or water interventions alone.

Collected data would be used immediately to inform and direct policy, engendering a much wider appreciation of the role of monitoring in the helping the poorest people to maintain and improve their livelihoods.




*Role of monitoring in improving response to the downward spiral of drought and water insecurity (from Calow et al., 2002, reporting on a UK aid project studying water security in drought-prone areas of Africa with partners from Ethiopia, Ghana, Malawi and South Africa.).*

slim needs to be re-evaluated pragmatically in order to at least continue providing a basic level of surveillance (Box 48).
Finally, the need for an integrated approach to monitoring design and resource management becomes even more important when dealing with transboundary aquifers, where the already complex interplay of geology, climate and human activities that defines a groundwater catchment is further complicated by political and legal differences of two or more neighbouring countries (Figures 26; 27).

As the UN/ECE Task Force on Monitoring and Assessment points out:

- monitoring of groundwater and surface water, of water quality and of quantity are often performed by different authorities, so the resultant information needs to be assessed in combination;

- the effects of groundwater and surface water interaction can be sensitive, especially when recharge is through seepage of (possibly highly polluted) surface waters, or in the case of vulnerable near-border ecosystems;

- there will be a rather wider variety of potential uses and users of the monitoring data than would be found with an aquifer wholly contained within one country, and this places an even greater than usual premium on the provision of unambiguous well-documented data. For example, the use of mutually agreed indicators of water level and water quality will not only help keep the range of parameters within manageable limits but also will foster convergence, at the technical level, at least in identifying and assessing a particular transboundary groundwater problem. The ability to work from a jointly agreed set of facts is a precondition for meaningful negotiations (at a political level) to resolve a given transboundary water issue and the provision of clear, focussed and uncontested groundwater monitoring data a prime component of such an array of facts.

*References*
*Bibliography (pp.120-125) numbers 4, 5, 19, 20, 21, 22, 23, 29, 35, 41, 78, 89, 90, 97, 102, 106 and 110 have been used in the production of this chapter.*

# 9 BIBLIOGRAPHY

The following books are recommended for further reading, providing additional information to the chapters indicated.

**Chapter 1**
Black, M. 1994. *Mega-slums: the coming sanitary crisis.* (London: WaterAid.)
Briscoe, J. 1993. When the cup is half full. *Environment,* Vol. 35(4) 7–37.
Gleick, P. 2002. *The World's Water 2002–2003: The biennial report on freshwater resources.* (Washington DC, USA: Island Press.)
Postel, S. 1984. *Water: rethinking management in an age of scarcity.* Worldwatch Paper, No. 62, (Washington DC, USA: Worldwatch.)

**Chapter 2**
Price, M. 1996**.** *Introducing groundwater*. Second edition. (London: Chapman and Hall.)

**Chapter 4**
Chapman, D. 1996**.** *Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring*. UNESCO/WHO/UNEP publication. (London: E & F N Spon.)
National Research Council (NRC). 1993. *Groundwater vulnerability assessment: predicting relative contamination potential under conditions of uncertainty.* Committee on Techniques for Assessing Groundwater Vulnerability, Water Science and Technology Board, Commission on Geosciences, Environment and Resources, NRC. National Academy Press (Washington DC, USA: NRC.)
West, J M, Pedley, S, Baker, S J, Barratt, L, Morris, B L, Storey, A, Ward, R S, and Barrett, M. 1998**.** A review of the impact of microbiological contaminants on groundwater. *EA R&D Technical Report* P139, (Bristol, UK: Environment Agency.)
Vrba, J, and Zaporozec, A. 1994. *Guidebook on mapping groundwater vulnerability*. International Association of Hydrogeologists International Contributions to Hydrogeology, Vol. 16. (Hannover, Germany: Heise.)

**Chapters 5-7**
*Protecting groundwater for health: managing the quality of drinking-water sources.* (Geneva: WHO.)
British Medical Association. 1992. *The BMA guide to pesticides, chemicals and health.* (London: E Arnold.)

**Chapter 8**
Department for International Development. 2000. *Achieving sustainability: poverty elimination and the environment* and *Addressing the water crisis: healthier and more productive lives for poor people.* Target Strategy Papers available from http://www.dfid.gov.uk.
Gleick, P. 2002. *The World's Water 2002-2003: the biennial report on freshwater resources*. (Washington DC, USA: Island Press.)
UNEP and WHO. 1996. *Water quality monitoring: a practical guide to the design and implementation of freshwater quality studies and monitoring programmes.* Bartram, J, and Balance, R (editors). (London: E & F N Spon.)

***Numbered references:*** these have been used in the compilation of individual chapters and are listed at the end of each chapter. Those marked * arise from groundwater-related technical assistance and applied research projects supported by the UK Department for International Development since 1985.

1 Acreman M, C, and Adams, B. 1998. Low flows, groundwater and wetland interactions—a scoping study. Report to the Environment Agency (W6-013), UKWIR (98/WR/09/1) and NERC (BGS WD/98/11).

* 2 Adams, B, and MacDonald, A M. 1998. Aquifer susceptibility to side-effects of groundwater exploitation. 71–76 in Groundwater pollution, aquifer recharge and vulnerability. Robins, N S (editor). *Geological Society of London Special Publications*, No. 130. ISBN1-897799-98-5.

* 3 Adams, B, Shearer, T R, Grimble, R, Brown, D, and Morton, J. 1996. The Yao Ba Oasis environment project china: final report. *British Geological Survey Technical Report*, WC/96/34. (Keyworth, Nottingham UK: BGS.)

4 Allan, J A. 1996. Water security policies and global systems for water scarce regions. *Proceedings of the International Commission on Irrigation and Drainage*, Sixteenth Congress, Cairo 1996.

5 Allan, J A. 2001. *The Middle East water question: hydropolitics and the global economy.* (London and New York: I B Tauris.)

6 Anon, 2003. The Great Man-made River Project [on line]. Available from: http://www.gmrp.org/index_en.html.

7 Arenas, J M, Carrero, G, Galache, J, Mediavilla, C, Silgado, A, and Vazquez, E M. 2001. Actuaciones realizadas tras el accidente de Aznacollar. *Boletin Geologico y Minero Especial*: 35–56.

* 8 ARGOSS. 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. *British Geological Survey Commissioned Report*, CR/01/142. (Keyworth, Nottingham UK: BGS.)

* 9 ARGOSS. 2002. Assessing risk to groundwater from on-site sanitation: scientific review and case-studies. *British Geological Survey Commissioned Report*, CR/02/079N. (Keyworth, Nottingham, UK: BGS.)

10 Armienta-Hernandez, M A, and Rodriguez-Castillo, R. 1995. Environmental exposure to chromium compounds in the Valley of Leon, Mexico. *Environmental Health Perspectives*, Vol. 103, 47–51.

11 Bhutta, M N, and Chaudhry, M R. 1999. Achievements and issues in 20th century in waterlogging and salinity. 141–153 *in Water resources achievements and issues in 20th century and challenges for the next millenium*. Chandio and Yasmin (editors). (Islamabad: Pakistan Council for Research on Water Resources.)

12 Booth, C J. 2002. The effects of longwall coal mining on overlying aquifers. 1–16 in Mine water hydrogeology and geochemistry. Younger, P L and Robins, N S (editors). *Geological Society of London Special Publication*, No. 198, 1–16.

13 Booth, C J, Curtiss, A M, and Miller, J D. 1994. Groundwater response to longwall mining, Saline County, Illinois USA. Proceedings of the fifth International Mine Water Congress, Nottingham (UK), September 1994.

14 Bouwer, H, and Rice, R C. 1984. Renovation of waste water at the 23rd Avenue rapid-infiltration project. *Journal of Water Pollution Control Federation*, Vol. 56, 76–83.

* 15 British Geological Survey, Comision Nacional del Agua, Sistema de Agua Potable y Alcantarillado del Municipio de Leon and Universidad Autonoma de Chihuahua. 1996. Effects of waste water reuse on urban groundwater resources of León, Mexico. *British Geological Survey Technical Report*, WD/95/64. (Keyworth, Nottingham, UK: BGS.)

* 16 British Geological Survey, Overseas Development Administration, United Nations Environment Programme and World Health Organisation. 1996. Characterisation and assessment of groundwater quality concerns in Asia–Pacific region UNEP/DEOA/AR.96-1. (Nairobi, Kenya: UNEP-DEIA.)

* 17 British Geological Survey and Cooperativa de Servicios Públicos 'Santa Cruz' Ltda. 1997. Assessment of pollution risk to deep aquifers from urban waste waters: Santa Cruz City Report. *British Geological Survey Technical Report*, WC/97/11. (Keyworth, Nottingham, UK: BGS.)

* 18 British Geological Survey, Thailand Department of Mineral Resources and Prince of Songkhla University. 1997. Assessment of pollution risk to deep aquifers from rrban waste waters: Hat Yai City Report. *British Geological Survey Technical Report*, WC/97/16. (Keyworth, Nottingham, UK: BGS.)

19 Brookshire, D S, and Whittington, D. 1993. Water resources issues in developing countries. *Water Resources Research*, Vol. 29, No. 7, 1883–1888.

20 Burke, J, Sauveplane, C, and Moench, M. 1999. Groundwater management and socio-economic responses. *Natural Resources Forum 23*, 303–313.

* 21 Calow, R C, Morris, B L, Macdonald, D M, Talbot, J C, and Lawrence, A R. 1999. Tools for assessing and managing groundwater pollution threats in urban areas. *British Geological Survey Technical Report*, WC/99/18. (Keyworth, Nottingham, UK: BGS.)

* 22 Calow, R C, Allan, J A, Merrett, S, MacDonald, A M, and Brown, D A. 2001. Sustainable management of the West Bank and Gaza aquifers: management options study inception report. *British Geological Survey Commissioned Report*, CR/01/258.

* 23 Calow, R C, MacDonald, A M, Nicol, A L, Robins, N S, and Kebede, S. 2002. The struggle for water: drought, water security and rural livelihoods. Final Report. *British Geological Survey Technical Report*, CR/02/226N. (Keyworth, Nottingham, UK: BGS.)

24 Chapman, D (editor). 1996. *Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring*. Second edition. UNESCO/WHO/UNEP publication. (London: E & F N Spon.)

25 Chéné , J M, 1996. Planning and managing urban water needs: the new challenge. In: *Managing water resources for large cities and towns,* HABITAT II Conference of 18-21 March 1996, Beijing China. (Nairobi, Kenya: UN Centre for Human Settlements.)

26 Chilton, P J. 1996. Chapter 9 Groundwater. In *Water quality assessments-a guide to the use of biota, sediments and water in environmental monitoring*. UNESCO/WHO/UNEP publication. (London: E & F N Spon.)

* 27 Chilton, P J, Vlugman, A A, and Foster, S S D. 1990. A groundwater pollution risk assessment for public water supply sources in Barbados in tropical hydrology and Caribbean Water Resources AWWA July 1990.

* 28 Chilton, P J, Jegat, H J, and Stuart, M E. 1995. Groundwater and agriculture: the interrelationship. Proceedings of an international seminar, Merida, Venezuela, October 1992. *British Geological Survey Technical Report*, WD/95/26. (Keyworth, Nottingham, UK: BGS.)

* 29 Chilton, P J, and Foster, S S D. 1996. Monitoring for groundwater quality assessment: current constraints and future strategies. In Proceedings of Monitoring Tailor-made II, Sept 1996, Nunspeet, Netherlands.

* 30 Chilton, P J, Stuart, M E, Escolero, O, Marks, R J, Gonzales, A, and Milne, C J. 1998. Groundwater recharge and pollution transport beneath waste water irrigation: the case of León, Mexico. 153–168 in Groundwater pollution, aquifer recharge and vulnerability. Robins N S (editor). *Geological Society of London Special Publication*, No. 130.

* 31 Chilton, P J, Stuart, M E, Lawrence, A R, Gooddy, D C, Williams, R J, and Johnson, A C. 2000. Assessing pesticide pollution of groundwater: current knowledge and remaining gaps. 17–25 in *Groundwater: past achievements and future challenges*. Sililo et al, (editors). (Rotterdam: Balkema.)

32 Choprapawon, C, and Ajjimangkul, S. 1999. Major interventions on chronic arsenic poisoning in Ronpibool district, Thailand—review and long term follow up. 355–362 in Chappell, W R, Abernathy, C O, and Calderon, R L. (editors). *Arsenic exposure and health effects.* (Amsterdam: Elsevier.)

33 Choprapawon, C, and Rodcline, A. 1997. Chronic arsenic poisoning in Ronpibool Nakhon Sri Thammarat, the Southern Province of Thailand. 69–77 in Abernathy, C O, Calderon, R L, and Chappell, W R. (editors). *Arsenic: exposure and health effects*. (London: Chapman & Hall.)

34 Christensen, T H, Kjeldsen, P, Albrechtsen, H-J, Heron, G, Nielson, Per H, Bjerg, P L, and Holm, P E. 1994. Attenuation of landfill leachate pollutants in aquifers. *Critical Reviews in Environmental Science and Technology*, Vol. 24(2), 119–202.

35 Clark, L. 2002. *Evaluation of urban pollution of surficial and groundwater aquifers in Africa*. Project DA/9999-00-01. (Nairobi, Kenya: UNEP Evaluation & Oversight Unit.)

36 Coombs, P, Morris, B L, and West, J M. 1999. *Transport and fate of Cryptosporidium and other pathogens in groundwater systems*. UKWIR Report 00/DW/06/11. (London, UK: Water Industry Research Ltd.)

37 Custodio, E. 2002. Aquifer overexploitation; what does it mean? *Hydrogeology Journal*, Vol. 10, 254–277.

38 Custodio, E, Guerra, J A, Jimenez, J, Medina, J A, and Soler, C. 1984. The effects of agriculture on the volcanic aquifers of the Canary Islands. *Environmental Geology*, Vol. 5(4), 225–231.

39 Davis, S N, and DeWiest, R J M. 1966. *Hydrogeology*. (New York: John Wiley & Sons.)

40 DEFRA. 2002. *Potential contaminants for the assessment of land. R&D Publication CLR8*. (Bristol, UK: Environment Agency.)

* 41 DFID. 2000. *Sustainable livelihoods guidance sheets*. (London, UK: Department for International Development.)

42 Dumpleton, S. 2001. The effects of coal mining on some hydraulic properties of the Sherwood Sandstone and drift in the Selby area, North Yorkshire, Unpublished PhD thesis, University of Sheffield, Department of Civil and Structural Engineering.

43 Dzhamalov, R G, and Zlobina, V L. 2001. Anthropogenic hydrogeological conditions in the Moscow city area, Russia. In Current problems of hydrogeology in urban areas. *Urban agglomerates and industrial centre*. Howard, K H F, and Israfilov, R G, (Dordrecht, Netherlands: Kluwer.)

44 EFE. 1998. Las aves migratorias de Francia, Holanda y Dinamarca, afectadas por el vertido toxico de Donana. Page 56 in ABC, Madrid.

45 Eiswirth, M, Wolf, L, and Hotzl, H. 2002. Balancing the contaminant input into urban water resources. In: Procs XXXII IAH and VI ALHSUD Congress on groundwater and human development. Mar del Plata 21-25 October 2002. (Mar del Plata, Argentina: UNIV National De Mar del Plata.)

46 Environment Agency. 1998. *Endocrine-disrupting substances in the environment: What should be done?* Consultative Report. (Bristol, UK: Environment Agency.)

* 47 Foster, S S D. 1992. Unsustainable development and irrational exploitation of groundwater resources in developing nations—an overview. *IAH Selected Papers*, Vol. 3, 321–336. (Hannover: VH Heise.)

48 Foster, S S D, and Hirata, R. 1988. *Groundwater pollution risk assessment: a methodology using available data*. (Lima, Peru: Pan American Centre for Sanitary Engineering and Environmental Sciences.)

* 49 Foster, S S D, Morris, B L, and Lawrence, A R. 1993. Effects of urbanisation on groundwater recharge. *Procs of ICE International conference on groundwater problems in urban areas*, London, June 1993. (London: Thomas Telford.)

* 50 Foster, S S D, Gale, I N and Hespanhol, I. 1994. Impacts of waste water use and disposal on groundwater. *British Geological Survey Technical Report*, WD/94/55. (Keyworth, Nottingham, UK: BGS.)

* 51 Foster, S S D, Lawrence, A R, and Morris, B L. 1998. Groundwater in urban development: assessing management needs and formulating policy strategies. *World Bank Technical Paper*, No. 390 (Washington DC: World Bank.)

* 52 Foster, S S D, Chilton, P J, Moench, M, Cardy, F, and Schiffler, M. 2000. Groundwater in rural development: facing the challenges of supply and resource sustainability. *World Bank Technical Paper*, No. 463 (Washington DC: World Bank), ISBN 0-8213-4703-9.

53 Freeze, R A, and Cherry, J A. 1979. *Groundwater*. (Englewood Cliffs NJ: Prentice Hall.)

54 Ghassemi, F, Jakeman, A J, and Nix, H A. 1995. *Salinisation of land and water resources*. (Sydney: University of New South Wales Press Ltd) ISBN 0 86840 198 6.

55 Gleick, P. 1998. *The World's Water 1998–1999: the biennial report on freshwater resources*. (Washington DC, USA: Island Press.)

56 Goldenburg, L C, Mandel, S, and Margaritz, M. 1986. Water-rock interaction at the mixing zone between chemically different bodies of groundwater—implications for management of sandy aquifers. *Hydrological Sciences Journal*, Vol. 31, 3, 9/1986, 413–425.

* 57 Gooddy, D C, Lawrence, A R, Morris, B L, and Chilton, P J. 1997. Chemical transformations of groundwater beneath unsewered cities. In Procs XXVII IAH Congress on groundwater in the urban environment, Nottingham, 21–27 September 1997. (Rotterdam: Balkema.)

58 Handa, B K. 1983. Effects of fertilizer use on groundwater quality in India. In: Groundwater in water resources planning. Proceedings of International Symposium, Koblenz.

59 Induambiente. 1999. No basta decir Adios. *Induambiente,* Vol. 39, 31. (Santiago, Chile.)

60 IPCC. 2001a. Climate change 2001. The scientific basis. Summary for policy makers. A report of Working Group I of the Intergovernmental Panel on Climate Change. Pub. IPCC.

61 IPCC. 2001b. Climate change 2001. Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. McCarthy, J J, Canziani, O F, Leary, N A, Dokken, D J, and White, K S. IPCC.

62 IWASRI. 1995. Effect of groundwater use on soil properties and agricultural development in salinity control and reclamation projects in Pakistan*. International Waterlogging and Salinity Research Institute, Publication*, No. 156 (Lahore: IWASRI.)

63 IWT. 1994. Water pollution due to leather industries in Tamil Nadu. 181–220 in *International water tribunal: the case books: pollution*. (Utrecht: International Books.)

64 Jones, P D, New, M, Parker, D E, Martin, S, and Rigor, I G. 1999. Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, Vol. 37, 173–199.

65 Karnchanawong, S, Koottatep, S, and Ikeguchi, T. 1993. Monitoring and evaluation of shallow well water quality near a waste disposal site. *Environmental International*, Vol. 19, 579–587.

66 Kavalanekar, N B, Sharma, S C, and Rushton, K R. 1992. Over-exploitation of an alluvial aquifer in Gujarat, India. *Hydrological Sciences Journal*, Vol. 37 (4).

67 Kinniburgh, D G, Gale, I N, Smedley, P L, Darling, W G, West, J M, Kimblin, R T, Parkrer, A, Rae, J E, Aldous, P J, and O'Shea, M J. 1994. The effects of historic abstraction of groundwater from the London Basin aquifers on groundwater quality. *Applied Geochemistry*, Vol. 9(2), 175–196.

* 68 Klinck, B A, Crawford, M C, and Noy, D J. 1995. A groundwater hazard assessment scheme for solid waste disposal. *British Geological Survey Technical Report*, WC/95/7. (Keyworth, Nottingham, UK: BGS.)

* 69 Klinck, B A, Stuart, M E, Ramnarong, V, Buapeng, S, and Sinpool-Anant, S. 1999. Human risk in relation to landfill leachate quality: case studies from Thailand*. British Geological Survey Technical Report*, WC/99/15. (Keyworth, Nottingham, UK: BGS.)

* 70 Klinck, B A, Hawkins, M P, Moore, Y, Ngorima, C, Kelm, U, Palumbo, B, and Lee, J-S. 2002. The environmental impact of metalliferous mining: Korea, Chile and Zimbabwe case studies. *British Geological Survey Technical Report*, CR/02/190N. (Keyworth, Nottingham, UK: BGS.)

71 Korte, N E. 1991. Naturally occurring arsenic in groundwater of the Midwestern United States. *Environmental Geology Water Sciences*, Vol. 18, 137–141.

* 72 Krishnasamy, K V, Ravichandran, S, Tamilselvan, C, Lawrence, A R, and Stuart, M E. 1993. Impact of agriculture on groundwater quality in the alluvial aquifers of Madras, India-Final Report. *British Geological Survey Technical Report*, WD/93/18. (Keyworth, Nottingham, UK: BGS.)

73 Krothe, J N, Garcia-Fresca, B, and Sharp, Jr. J M. 2002. Effects of urbanisation on groundwater systems. 45 in Procs XXXII IAH and VI ALHSUD Congress on groundwater and human development. 21-25 October 2002. (Mar del Plata, Argentina: Univ National de Mar del Plata.)

74 Lagerstedt, E, Jacks, G, and Sefe, F. 1994. Nitrate in groundwater and nitrogen circulation in eastern Botswana. *Environmental Geology*, Vol. 23, 0–64.

75 Lawrence, A R, and Foster, S S D. 1987. The pollution threat from agricultural pesticides and industrial solvents. *BGS Hydrogeology Group Research Report*, 87/2. (Wallingford, UK: BGS.)

* 76 Lawrence, A R, Morris, B L, Gooddy, D C, Calow, R, and Bird, M J. 1997. The study of the pollution risk to deep groundwater from urban waste waters: project summary report. *British Geological Survey Technical Report*, WC/97/15. (Keyworth, Nottingham, UK: BGS.)

77 Lawrence, A R, and O'Dochartaigh, B E. 1998. *Groundwater contamination in perspective*. (Keyworth, Nottingham, UK: British Geological Survey.)

78 Machiavelli, N. 1513. *The Prince*, 1513. Dover Thrift Edition 1992 (New York, USA Dover Publications.)

79 Maidment, D R (editor). 1992. *Handbook of hydrology*. (New York: McGraw-Hill.)

80 Meinzer, O E. 1923. Outline of ground-water hydrology with definitions. *US Geological Survey Water Supply*, Paper 494. (Washington: USGS.)

* 81 Morris, B L, Lawrence, A R, and Stuart, M E. 1994. The impact of urbanisation on groundwater quality (Project Summary Report). *British Geological Survey Technical Report*, WC/94/56. (Keyworth, Nottingham, UK: BGS.)

* 82 Morris, B L, Litvak, R G, and Ahmed, K M. 2001. Urban groundwater protection and management lessons from 2 developing city case studies in Bangladesh and Kyrghyzstan. In: Current problems of hydrogeology in urban areas, urban agglomerates and industrial centres, Proceedings of NATO Advanced Science Workshop, Baku Azerbaijan, June 2001 NATO Science Series IV, Vol. 8, Kluwer Dordrecht.

* 83 Morris, B L, Tyson, G, Foster, S S D, Lawrence, A R, and Calow, R C. 2001. Groundwater in urban development: a guide to data acquisition and system characterisation [on line]. Website material provided for World Bank on www.worldbank.org. Available from: http://lnweb18.worldbank.org/ESSD/essdext.nsf/18ByDocName/SectorsandThemesGroundwaterGroundwaterinUrbanDevelopment.

* 84 Morris, B L, Seddique, A A, and Ahmed, K M. In press. Response of the Dupi Tila aquifer to intensive pumping in Dhaka Bangladesh. *Hydrogeology Journal*.

* 85 Mubarak, A M, Gunawardhana, H P G, Abeyratne, D J, Kuruppuarachchi, D S P, Fernando, W A R N, Lawrence, A R and Stuart, M E. 1992. Impact of agriculture on groundwater quality: Kalpitya Peninsula, Sri Lanka. *British Geological Survey Technical Report*, WD/92/49.

86 Muthu, P. 1992. Tannery pollution in Tamil Nadu. *Waterlines*, Vol. 11 (1) 6–8.

87 Nagarajah, S, Emerson, B N, Abeykoon, V, and Yogalingam, S. 1988. Water quality of some wells in Jaffna and Kilinochchi with special reference to nitrate pollution. *Tropical Agriculturalist*, Vol. 144, 61–78.

88 National Rivers Authority. 1994. Abandoned mines and the water environment. *Water Quality Series Report*, No. 14. (Bristol: NRA.)

89 Ohlsson, L. 1999. Environment, scarcity and conflict a study of Malthusian concerns. PhD dissertation, Department of Peace and Development Research, University of Goteborg.

90 Ohlsson, L, and Turton, A R. 1999. The turning of the screw: social resource scarcity as a bottleneck in adaptation to water scarcity. Occasional Paper No.19, SOAS Water Issues Group, University College London.

91 Pain, D J A, Sanchez, and Meharg, A A. 1998. The Donana ecological disaster: contamination of a world heritage estuarine marsh ecosystem with acidified pyrite mine waste. *The Science of the Total Environment*, Vol. 222, 45–54.

92 Pescod, M B. 1992. Waste water treatment in agriculture. *Irrigation and Drainage*. Paper, 47. (Rome: FAO.) ISBN 92-5-103135-5.

93 Poland, J F (editor). 1984. *Guidebook to studies of land subsidence due to groundwater withdrawal*. (Paris: UNESCO.)

94 Postel, S. 1999. *Pillar of sand: Can the irrigation miracle last?* (New York: WorldWatch/Norton.) ISBN 0-393-31937-7.

95 Price, M. 1996. *Introducing groundwater*. Second edition. (London: Chapman and Hall.)

96 Prokopovich, N P. 1976. Some geologic factors determining land subsidence. *Bull. Int. Association of Engineering Geology*, No. 14 Krefeld, West Germany. 75–81.

97 Puri, S, Appelgren, B, Arnold, G, Aureli, A, Burchi, S, Burke, J, Margat, J, and Pallas, P. 2001. Internationally shared (transboundary) aquifer resources management—their significance and sustainable management: a framework document. IHP-VI, IHP Non-serial *Publications in Hydrology* SC-2001/WS/40. (Paris: UNESCO.)

98 Robinson, H D. 1996. A review of the composition of leachates from domestic wastes in landfill sites. CWM-072-95, Department of the Environment (DoE), Wastes Technical Division, UK. Technical Aspects of Controlled Waste Management Series.

99 Rushton, K R, and Al-Othman, A A R R. 1993. Control of rising groundwater levels in Riyadh, Saudi Arabia. 299–309 *in Procs of ICE International conference on groundwater problems in urban areas*, London, June 1993. (London: Thomas Telford.)

100 Sampat, P. 2000. Deep trouble: the hidden threat of groundwater pollution. *Worldwatch Paper*, No. 154, (Washington DC: Worldwatch Institute.)

101 Siripitayakunkit, Visudhipan, U P, Pradipasen, M, and Vorapongsathron, T. 1999. Association between chronic arsenic exposure and children's intelligence in Thailand. 141–149 in *Arsenic exposure and health*. Chappell, W R, Abernathy, C O, and Calderon, R L. (editors). (Amsterdam: Elsevier.)

102 Start, D. 2001. The rise and fall of the rural non-farm economy: poverty impacts and policy options. 491–505 in *Development policy review*, 2001, 19 (4). Theme issue, rethinking rural development. Ashley, C, and Maxwell, S (London: ODI.)

103 Straskraba, V, Frank, J, Bosworth, W C, and Swinehart, T W. 1994. Study of the impacts of a longwall coal mining operation on surface and ground water resources at the Windsor Mine, West Virginia, USA. Proceedings, 5th International Mine Water Congress, Nottingham (UK), September 1994.

* 104 Stuart, M E, and Klinck, B A. 1998. A catalogue of leachate quality for selected landfills from newly industrialised countries. *British Geological Survey Technical Report*, WC/98/49. (Keyworth, Nottingham, UK: BGS.)

105 Sweeney J, Hart, P A, and McConvey, P J. 1998. Investigation and management of pesticide pollution in the Lincolnshire Limestone aquifer in Eastern England. Groundwater contaminants and their migration. Mather, J, Banks, D, Dumpleton, S, and Fermor, M (editors). *Geological Society of London Special Publication*, No. 128, 63–74.

106 Swyngedouw, E. 1999. Sustainability, risk and nature: the political ecology of water in advanced countries. Proceedings of a workshop convened at the University of Oxford, 15–17 April 1999.

107 Teaf, C, Merkel, B, Mulisch, H-M, Kuperberg, M, and Wcislo, E. In press. Chapter 10 Industry, mining and military sites: information needs. In: *Protecting groundwater for health: managing the quality of drinking-water sources*. (Geneva: WHO.)

108 Thewsey, M personal communication 30 July 2002.

109 UN Division for Sustainable Development. 2002. [on line].
Available from: http://www.un.org/esa/sustdev/agenda21chapter1 8.htm.

110 UN/ECE Task Force on Monitoring and Assessment. 2000. *Guidelines on monitoring and assessment of transboundary groundwaters*. (Netherlands: UN-ECE Lelystad.)

111 UNEP. 1996. *Groundwater: a threatened resource*. UNEP Environment Library, No.15. (Nairobi, Kenya: UNEP.)

112 Vázquez-Suñé, E, Sanchez-Vila, X, Carrera, J, and Marizza, M. 1997. Rising groundwater levels in Barcelona: evolution and effects on urban structures. In: Procs XXVII IAH Congress on groundwater in the urban environment, Nottingham, 21-27 September 1997. (Rotterdam: Balkema.)

113 Walton, N R G. 1997. Rising groundwater breaks surface: a case-study from the Arabian Gulf. In: Procs XXVII IAH Congress on groundwater in the urban environment, Nottingham, 21-27 September 1997. (Rotterdam: Balkema.)

114 West, J M, Pedley, S, Baker, S J, Barratt, L, Morris, B L, Storey, A, Ward, R S, and Barrett, M. 1998. A review of the impact of microbiological contaminants on groundwater. *EA R&D Technical Report*. (Bristol: Environment Agency.)

115 WHO. 1989. Health guidelines for the use of waste water in agriculture and aquaculture. *Technical Report*, 778. (Geneva: WHO.)

116 WHO. 1998. *Guidelines for drinking-water quality*. Second edition. Vol. 2 and Addendum to Vol. 2 (Geneva: WHO.)

117 Williams, M. 2001. Arsenic in mine waters: an international study. *Environmental Geology*, Vol. 40, 267–279.

118 Williams, M F, Fordyce, Paijitprapapon, A, and Charoen-Chaisri, P. 1996. Arsenic contamination in surface drainage and groundwater in part of the southeast Asian tin belt, Nakhon Si Thammarat Province, southern Thailand. *Environmental Geology*, Vol. 27, 16–33.

* 119 Williams, T M. 1997. UK Department for International Development project R6491: environmental arsenic exposure (sub-programme—mining related arsenic hazards.) Thailand case study summary report. *British Geological Survey Overseas Geological Series Technical Report*, WC/95/06.

* 120 Wood, B P, and Chilton, P J. 1995. The occurrence and distribution of ametryne, atrazine and its deethylated metabolite in Barbados' groundwater. In Groundwater and agriculture: the interrelationship. Procs of International Seminar in Mérida Venezuela, 14–17 Oct 1992. Chilton, P J, Jegat, H J, and Stuart, M E (editors). *British Geological Survey Technical Report*, WD/95/26. (Keyworth, Nottingham, UK: BGS.)

121 World Bank. 2002. Poverty and climate change. Reducing the vulnerability of the poor. Draft Report for consultation [on line]. [cited 15 January 2003] Available from: http://lnweb18.worldbank.org/ESSD/essdext.nsf/46ByDocName/KeyThemesVulnerabilityandAdaptationPovertyandClimateChange.

122 World Bank and World Resources. 2000–2001. People and ecosystems-the fraying web of life. United Nations Development Programme, United Nations Environment Programme, World Bank and World Resources Institute, Washington, DC, USA.

123 Young, R A. 1992. Managing aquifer over-exploitation: Economics and policies. 199–222 in *Selected papers on overexploitation*. Simmers, Villarroya and Rebollo (editors) (Hanover, Germany: IAH Heise.) Vol. 3.

124 Younger, P L, and Robins, N S. 2002. Challenges in the characterization and prediction of the hydrogeology and geochemistry of mined ground. 1–16 in *Mine water hydrogeology and geochemistry*. Younger, P L, and Robins, N S (editors). *Geological Society of London Special Publication*, No. 198.

# INDEX


www.unep.org

United Nations Environment Programme
P.O. Box 30552, Nairobi 00100, Kenya
Tel: (254 2) 624105
Fax: (254 2) 624269
E-mail: dewainfo@unep.org
Web: www.unep.org
www.unep.net


UNEP

For further information


Division of Early Warning and Assessment
United Nations Environment Programme
P.O. Box 30552, Nairobi 00100, Kenya
Tel: (254-2) 624028 Fax: (254-2) 623943
Email: dewa.director@unep.org
Web: www.unep.org, www.unep.net