UNEP Environment Library No 15

GROUNDWATER: A THREATENED RESOURCE

United Nations Environment Programme
Groundwater: a threatened resource
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The UNEP GEMS/Water Programme and the Environment Library

Since 1976, UNEP has participated in worldwide efforts to assess and improve freshwater quality by managing the Global Environment Monitoring System's Water Programme (GEMS/Water). GEMS/Water was launched by UNEP as a joint effort with three other United Nations agencies: the World Health Organization (WHO), the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the World Meteorological Organization (WMO). GEMS/Water is a global programme dealing mainly with water quality monitoring and assessment. Some 60 nations participate in its global network of stations which monitor water quality in rivers, lakes, reservoirs and groundwater. UNEP is also working on means of improving the use made of the data collected for water resource management.

The programme operates jointly with a number of Collaborating Centres including the Danish Water Quality Institute, the British Geological Survey and the Robens Institute in the United Kingdom, and the National Water Research Institute in Canada. These centres constitute the scientific backbone of the monitoring and assessment activities.

UNEP/GEMS started its Environment Library series in 1987 in order to disseminate environmental information on major topics to a non-technical audience. This is the 15th volume in the series and the 4th volume on water issues. The other three are *Freshwater Pollution, The Pollution of Lakes and Reservoirs* and *Water Quality of World River Basins*.

Contents

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Foreword

The world's water is one of our most precious resources. Lack of water is one of the principal causes of delayed development. Polluted water is one of the biggest killers we know, responsible for up to 27 000 deaths a day in the world's poorest countries.

Of the limited volume of freshwater that is available to us, some 97 percent (excluding permanently frozen water) is stored underground. More than 1500 million people rely on this groundwater for their drinking water. Farmers all over the world use it to irrigate their crops. In arid areas, where rainfall is low or virtually non-existent, groundwater may be the only source of water for the human population.

As populations grow and their need for water increases, the pressures on our groundwater resources also increases. In many areas of the world, groundwater is now being over-abstracted, in some places massively so. The result is falling water levels and declining well yields, more expensive supplies, land subsidence, the intrusion of salt water into freshwater supplies and ecological damage such as the drying out of wetlands.

Groundwater is also being polluted. Cities with poor sanitation systems are allowing foul water to seep into underground aquifers, whence it eventually contaminates the boreholes and wells that supply drinking water. Industries accidentally spill or release their effluents into the ground or into surface water courses whence pollution is carried deep underground. Chemical fertilizers and pesticides are leached through the soil and down into the aquifers as a result of the intensification of agriculture.

The end result is a serious deterioration of groundwater quality. It is always extremely difficult and very costly to clean up a polluted aquifer. Often it is simply impossible. Because water flows so slowly underground, it takes many years or decades for pollution to show up. Many of the aquifers from which we are currently abstracting pure water may already be contaminated.

It is therefore urgent that we protect our groundwater supplies with diligence, and that everyone understands the importance of doing so. This publication is intended to explain to readers how important groundwater is, the extent of the threat to it, and the actions that can be taken to protect it.

Elizabeth Dowdeswell
Executive Director
United Nations Environment Programme

Overview

More intensive monitoring is required in almost all countries in order that a clearer picture is painted of the state of the world's aquifers and what must be done to preserve them for future generations.

Some 97 percent of all the freshwater that is found on the planet is stored underground (excluding water locked in the polar ice caps and glaciers). This vast water reserve, on which at least 1500 million people depend for their drinking water supply, is stored in the pores that exist in materials such as sand and gravel, and in the fractures that are found in rocks such as sandstone and limestone.

Groundwater supplies are recharged by rainwater that infiltrates down through the soil and the unsaturated layer below it. When rainwater reaches the water table and joins an aquifer, it begins a long and slow journey underground, moving at rates ranging from a few millimetres to a few metres a day. Eventually it finds an outlet, in a riverbed, a spring, a man-made well or straight to the sea.

Groundwater can be extremely old, and some is derived in part from rainwater that fell as long as 30 000 years ago. Many groundwater sources have supplied water for human consumption for several thousand years since the first human settlements were established around wells or springs.

Groundwater supplies are coming under increasing pressure from growing human populations that consume increasing amounts of water as development proceeds. One result is that many groundwater reserves, particularly in arid areas, are being over-exploited, with water being abstracted from them at unsustainable rates.

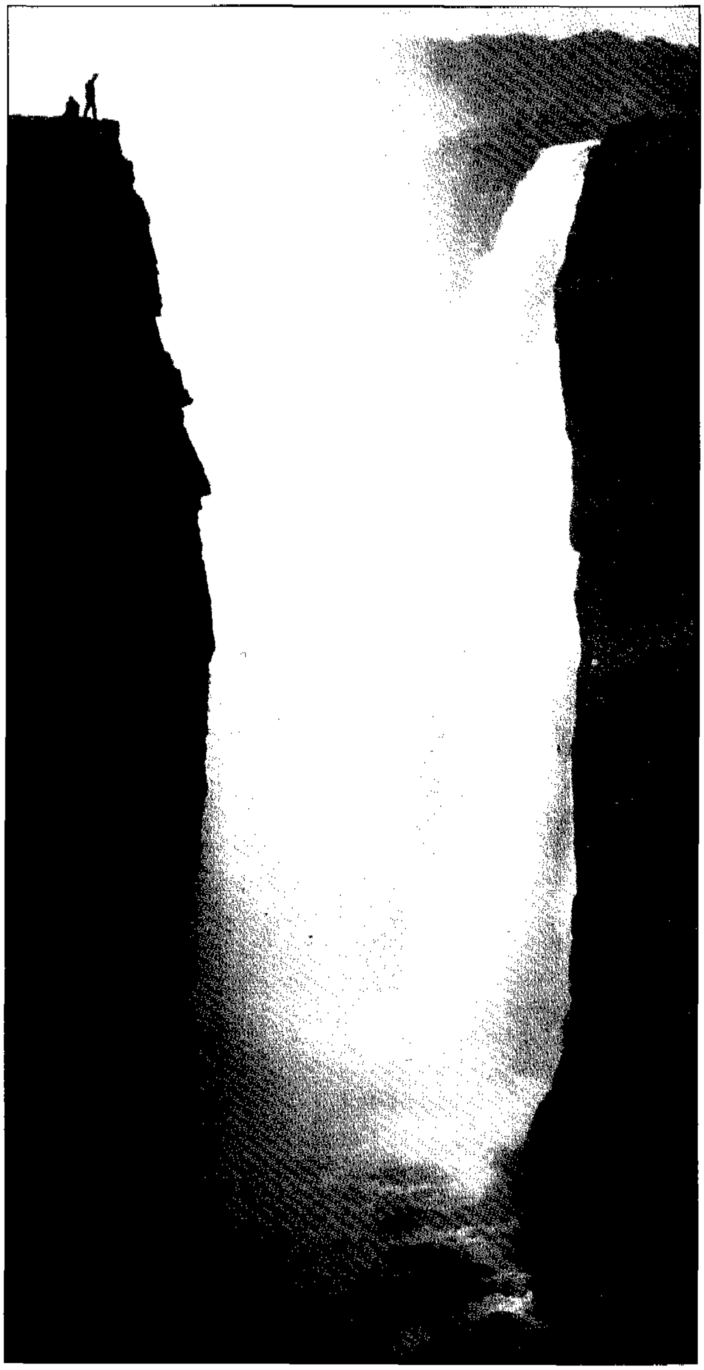
Over-abstraction causes a number of serious problems. Often yields from boreholes and wells are reduced, which ultimately increases the cost of pumping and thus the price of urban water supplies. As water levels fall, so may the ground settle. Land subsidence is now a major problem in many cities in developing countries, causing expensive damage to urban structures. Over-abstraction is also leading in many coastal areas to the intrusion of salt water into groundwater reserves many kilometres inland. In some inland areas, saline water from deep underground is rising in response to over-pumping.

Groundwater is also becoming increasingly polluted. One of the major sources is foul water and sewage from cities in developing countries with inadequate sanitation systems. In many urban aquifers, levels of nitrate are high and potentially dangerous micro-organisms are finding their way into wells and boreholes used for drinking water. Other chemicals are leached by the rain from rubbish tips and landfills, eventually finding their way into aquifers. Industry is also polluting groundwater, allowing liquid wastes to be released into the ground or into surface water courses and spilling chemicals such as hydrocarbon fuels and chlorinated solvents from leaking storage tanks. Mining, and disused mines where pumping has stopped, are further sources of pollution.

Agriculture is another source of groundwater pollution. Some of the chemical fertilizer and pesticide used in agriculture never reaches the plants for which it was intended. Instead it is washed by the rain from the soil and down into underground water reserves.

Groundwater pollution is insidious and expensive: insidious because it takes many years to show up in abstracted water, by which time it may be too late to prevent serious contamination; and expensive because the cost of providing alternative water supplies, and remediating polluted aquifers, is very high. Indeed, restoration to drinking water standards is often impossible.

For these reasons, there is a need to assess aquifer vulnerability and improve the protection of groundwater resources. Abstraction must be better controlled and land-use zoning controls introduced to protect the most vulnerable aquifers. More intensive monitoring is required in almost all countries in order that a clearer picture is painted of the state of the world's aquifers and what must be done to preserve them for future generations.



Shinichino Sawano/UNEP

While surface water sources are sometimes spectacular, they are tiny compared to the water resources stored underground.

The scientific background

The hydrogeological cycle

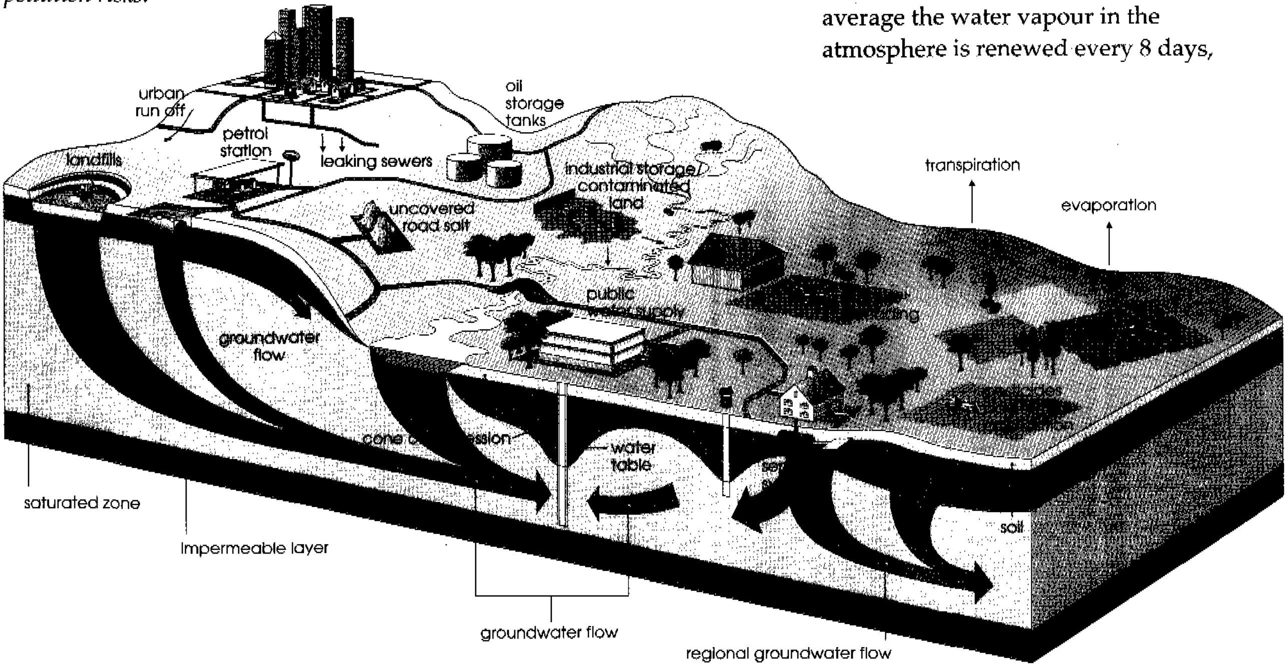
Some of the water in the Chalk aquifer that lies under London fell as rain as long ago as the last Ice Age.

Groundwater is water that accumulates underground. There is a lot of it. Of the 37 million km^3 of freshwater that is to be found on the planet, some 8 million km^3—roughly 22 percent—is stored underground in the form of groundwater. Excluding water locked in the polar ice caps, groundwater constitutes some 97 percent of all the freshwater that is potentially available for human use on or beneath the Earth's surface. The remainder is stored in lakes, rivers and swamps.

Groundwater reserves are recharged for the most part by rain that infiltrates through the soil into the underlying layers. These reserves are occasionally augmented by streams and rivers that lose water to the underground strata. Once underground, the water flows at rates ranging from more than 10 metres a day to as little as 1 metre a year, until it reaches an outlet. This may take the form of a spring or of a system of slow seepages at the ground surface. It is these seepages that keep rivers flowing during dry periods. In some places, a system of natural springs provides sufficient water to create a river. The River Touvre in central France, for example, is created by just such a system of springs which vent to the surface as much as 60 m^3 of water a second during times of maximum flow.

The time scales of groundwater flow are long. It may take years or even decades for water to find its way down through the soil to reach the water table, the level at which the ground is fully saturated. Once there, the water may remain underground for tens or even thousands of years before it reappears at the surface. Some of the water in the Chalk aquifer that lies under London fell as rain as long ago as the last Ice Age. According to one estimate, on average the water vapour in the atmosphere is renewed every 8 days,

Diagram of the hydrogeological cycle shows groundwater and surface water relationships, and groundwater pollution risks.



stream water every 16 days, soil moisture once a year, swamp water every 5 years and lake water every 17 years. The average for groundwater is 1400 years but the recycle time for some aquifers is much longer even than this.

Occasionally, geological events trap water underground, cutting it off from both its source of supply and its outlets. Climatic change may also deprive underground stores of any means of recharge, as has happened under a number of regions which are now desert but which were formerly much wetter.

Groundwater reserves which are not recharged are known as fossil water. Such water can be tapped and used through wells or boreholes but once the water is pumped out it may never be replenished. Examples of fossil water are found under the Saharan desert, for example, where plans for its intensive use have aroused fierce controversy from the countries that share the aquifer (see box on page 8).

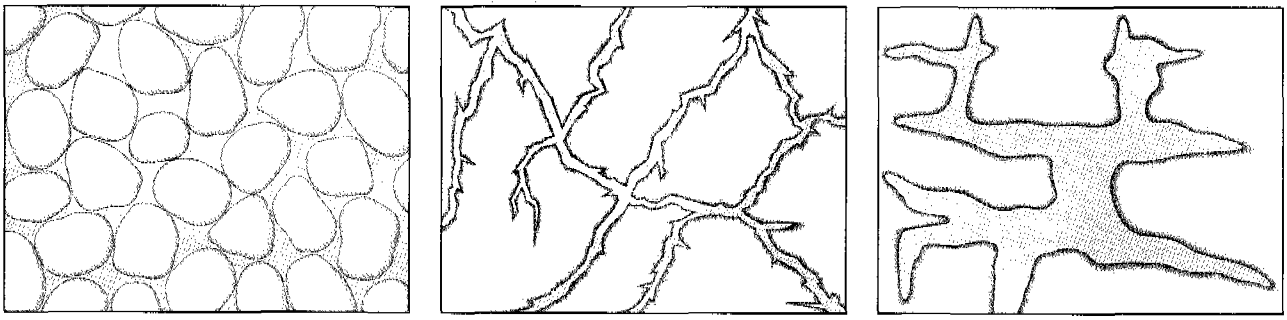
Water in aquifers

The water-bearing material in which groundwater is stored and through which it flows is called an aquifer. Aquifers can consist of unconsolidated materials such as sand and gravel, or consolidated rock such as sandstone. Unconsolidated materials can store large volumes of water. Sands, for example, can store up to 30 percent of their volume as water. Consolidated materials may also be very porous in that they can store large volumes of water but their pores are usually too small to allow the water to flow easily through the material. In some rocks the pores act as a form of unextractable water storage, unable to release their water because of the capillary attraction between the water and the pore surface.

However, consolidated materials also store water in tiny fractures in the rock. Although these fractures rarely occupy more than 1 percent of total volume, in rocks such as limestone they can become enlarged as the rock is dissolved away. These enlarged fractures enable the aquifer both to store large volumes of water and permit high rates of water movement (see illustration below).

The major aquifers in the United Kingdom are made of limestone or sandstone. They are extensive, covering an area of several

Unconsolidated materials such as sand (below left) can store up to 30 percent of their total volume as water. In consolidated rocks (below centre) water is stored only in fractures, and rarely exceeds 1 percent of total volume. In soft rocks such as limestone, however, these fractures are enlarged by solution and provide significant water storage (below right).



thousand square kilometres, and in places are more than 100 metres deep. The great limestone aquifer that lies under large areas of southern and eastern England, called the Chalk, is estimated to contain 2000 km^3 of water (compared to the 0.8 km^3 of water in the major water reservoirs of England and Wales). Though more water could be extracted from these aquifers, doing so could significantly reduce river flow in the area.

The great aquifers of the world, such as those that underlie the Ganges and Indus basins in south Asia, are of course much larger than the Chalk, and the total volume of water pumped from them is also much larger. The aquifer that lies under the 350 000 km^2 Huang-Hai-Hai Plain of eastern China, for example, provides drinking water for 160 million people and irrigates 20 million hectares of land.

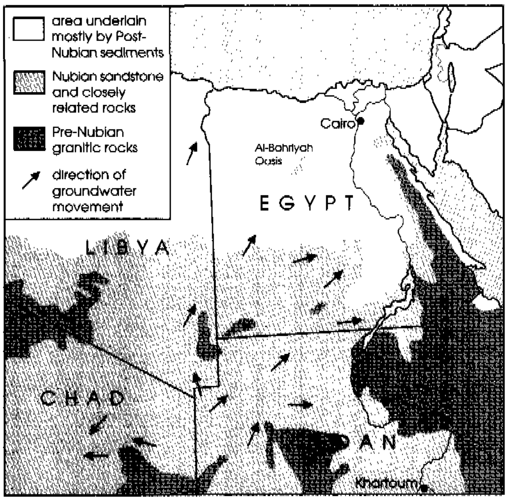
Aquifers are usually bounded above by an unsaturated zone, containing both air and water, and below by an impermeable bed of clay or rock. The boundary between the saturated and unsaturated areas is known as the water table. In arid areas, the water table may be as much as 100 metres below the surface while in more humid areas it can be close to the surface.

Some aquifers, however, are bounded entirely by impermeable layers and contain water under pressure. When wells are drilled down to such pressurized aquifers, the water will rise to the surface under its own pressure. In the Middle Ages a number of these pressurized aquifers were tapped in the ancient province of Artois (now the Pas-de-Calais) in France; these wells became so famous that all flowing wells were subsequently called artesian wells.

Fossil groundwater in the sub-Saharan aquifer

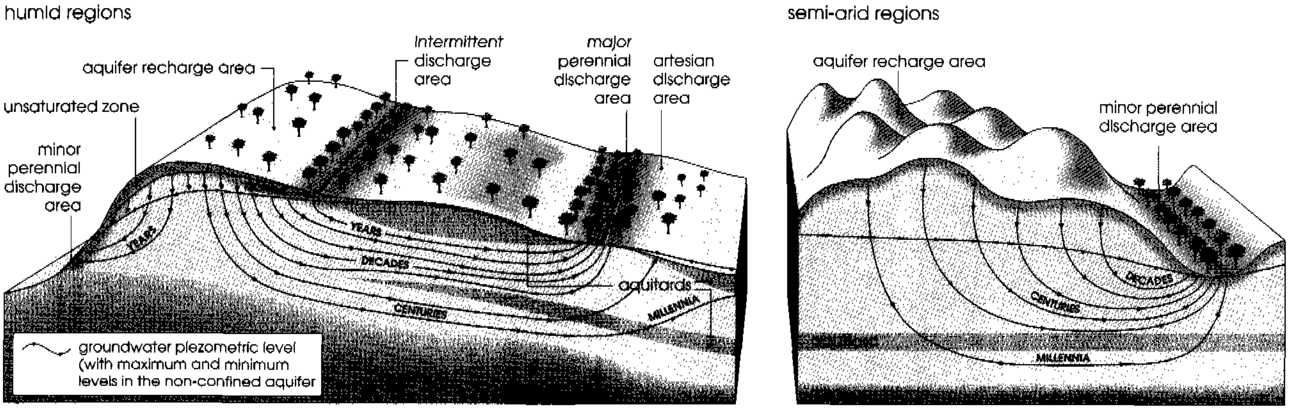
One of the world's most extensive aquifers lies under parts of Chad, Egypt, Libya and Sudan in the Sahara desert. This aquifer, of Nubian sandstone, has delivered water to many of the desert's oases for millennia. Water in the aquifer is renewed very slowly, and most of it has been in the aquifer for at least 30 000 years. It is essentially fossil water dating from a time when rainfall over north Africa was much higher than it is now.

Libya has an ambitious programme of pumping water from the aquifer to supply the populated coastal regions of the country, where overpumping of groundwater has diminished supplies and caused saltwater intrusion. A giant pipeline to do this, capable of carrying 730 million m^3 of water a year, was opened as the first phase of this programme in August 1991. By the end of the five-phase programme, estimated to cost US$25 000 million, the volume of water pumped from the aquifer every year will approach the flow rate of a large river—indeed, in Libya the project was named 'The Great Man-made River Project'.



Part of the sub-Saharan fossil aquifer; arrows show the direction of water movement.

How groundwater flows



Basic elements of groundwater flow in humid regions (left) and semi-arid regions (right).

Groundwater moves through aquifers as a result of differences in pressure or elevation of the water table within the aquifer and can be compared with movement of water through a pipe. As in pipes, various obstructions may occur as the water moves from the point of recharge to its exit from an aquifer. Some rock formations, such as shale, are so impermeable to water that they effectively stop groundwater flow completely; these are called aquicludes. Other geological strata, such as clay 'lenses' embedded with sand, may slow down the flow of water; these are called aquitards.

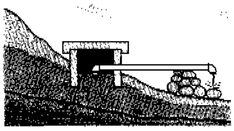
The rate at which water flows through an aquifer depends on the permeability and porosity of the rock, and on the pressure gradient. Limestone, for example, is highly permeable and limestone aquifers, such as those under southern England, Denmark and northern France, respond rapidly to changes in recharge and abstraction rates. Groundwater levels in such areas often fluctuate by as much as 10 metres a year, and can change by up to 50 metres a year.

Even so, groundwater flow rates are very small compared to those of surface water. The water abstracted from many of the deeper alluvial basins is likely to be thousands or even hundreds of thousands of years old. The slow movement of groundwater contributes greatly to its purity since contaminants become highly attenuated during groundwater's normally long journey from the surface, through the aquifer and into a borehole.

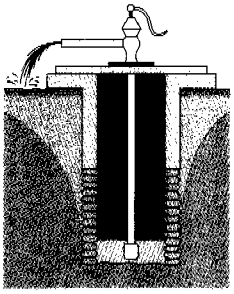
Salt water, as well as freshwater, can flow through rock. Near coastlines, saltwater intrusion can occur where the water table is lowered due to abstraction of fresh water, contaminating the aquifers for distances of several kilometres inland. Climatic change, resulting in rising sea levels, is likely to accentuate this problem.

The importance of groundwater

Early uses of groundwater



Lateral tapping of groundwater, the basis of the qanat system



Protected dugwell

Groundwater is used extensively by human populations on all continents. While many early populations settled by sources of water such as rivers and lakes, many others based settlements on the existence of a spring or a well—hence the common ending '-well' for place names in England and '-ac' for place names in France.

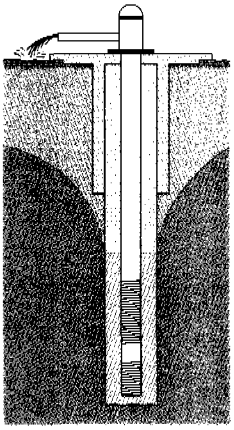
The earliest wells were probably built in the Near East where, although they were rarely deeper than 50 metres, they were often wide enough to accommodate a donkey path used to collect the water. The ancient Chinese developed slow drilling methods that enabled wells to be dug down to 1500 metres or so, using drilling techniques that continued for years or even decades.

Some 2500 years ago, the use of *qanats* was developed in Iran. These are long horizontal galleries connecting aquifers at the foot of mountains to fields and villages several kilometres away. The use of *qanats* spread as far afield as Egypt and Afghanistan, and many such systems are still used today.

Flowing or pressurized wells were first developed in Europe in Flanders in about 1100 A.D. where by that time a water wheel was being powered by four lined wells driven more than 100 metres down into a confined Chalk aquifer.

During the 20th century, both drilling and pumping technology developed so fast that it became easy to sink deep boreholes quickly, and to extract large volumes of water from them. While these developments have increased supplies of drinking and irrigation water, they have led to the rapid lowering of the water table under many cities and to the virtual exhaustion of some of the aquifers used to supply irrigation water in arid climates.

Where groundwater is used



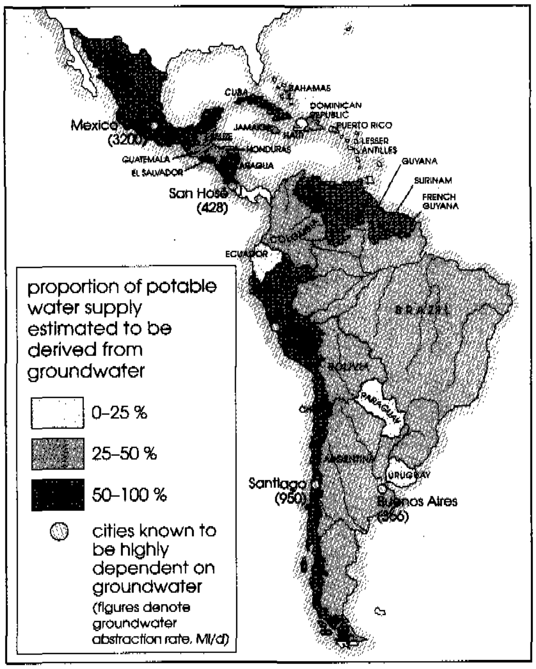
Borehole or tubewell

No authoritative estimates exist of the percentage of world water use that depends on groundwater. About one-third of Asia's population, some 1000–1200 million people, are thought to depend on groundwater. Some 150 million Latin Americans also depend on groundwater (see maps on page 11). Some individual countries, such as Barbados, Denmark and the Netherlands, depend almost entirely on groundwater. More than one-third of water use in France and the United Kingdom is supplied from aquifers and the United States is 50 percent dependent on groundwater.

Many of the world's most important cities, including Mexico City, Lima, Dhaka and Jakarta, for example, depend largely on groundwater. In Mexico City, the groundwater supply is from some 1500 boreholes supplying more than 3200 million litres a day. While groundwater supplies are of obvious importance to cities in arid areas, they are also extensively used in humid areas—largely because they provide water that requires little or no treatment and which can be cheaply developed.

It is often thought that recharge beneath cities is reduced as a result of covering the land surface with impermeable roads, parking areas and buildings. In fact, this is not so, particularly in cities that have inadequate sewerage systems. Recharge rates have been found to be up to six times higher in urban areas than in rural ones as a result initially of water being imported from peri-urban areas and then leaking into the ground from water mains, sewers and septic tanks, and soakaway drainage from homes and roads. This is particularly striking in one of the suburbs of Lima, a city situated in Peru's arid zone. There the natural recharge rate under pre-urban conditions would be zero. Today it is 700 mm a year, due largely to leaking water mains and over-irrigation of amenity areas.

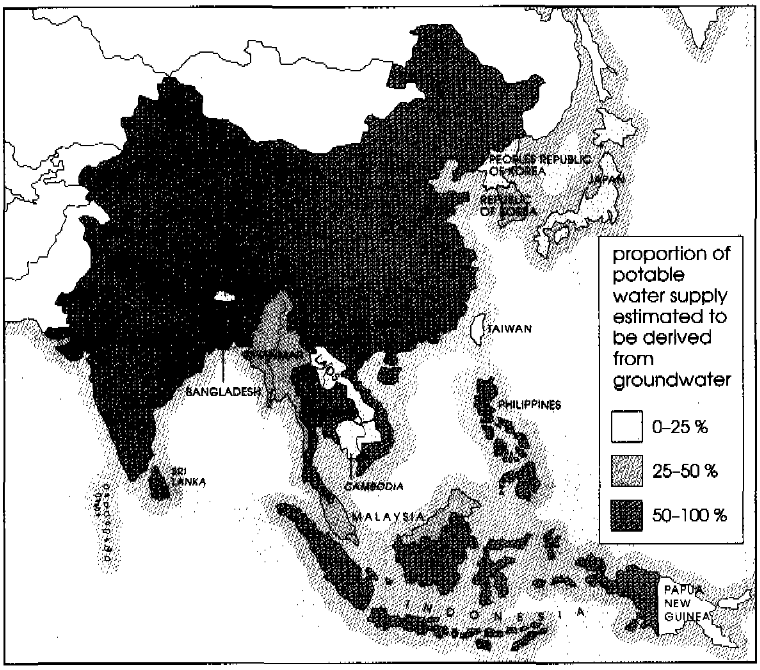
Groundwater now supplies more than 90 percent of the rural population in such countries as Costa Rica, El Salvador and Guyana. Rural communities often depend on low-yielding boreholes, producing perhaps only 0.5 to 5.0 litres a second (high-yielding boreholes used for irrigation and urban water supply can produce 20 times as much).



Groundwater use statistics are incomplete in most developing countries. The maps on the left and below provide estimates of the extent to which South and Central American and Asian populations depend on groundwater for domestic supplies.

British Geological Survey

Surface water courses often receive domestic and industrial effluent which may infiltrate to shallow groundwater.



The advantages of groundwater

> Whereas the development of surface reservoirs involves the construction of large and costly dams and reservoirs, groundwater can be developed as and when needed through the addition of boreholes and wells.

Groundwater has numerous advantages over surface water sources. First, its supplies are not subject to abrupt change as a result of abnormal weather. Whereas in some countries, an exceptionally hot and dry summer is sufficient to reduce surface reservoirs to dangerously low levels, groundwater supplies will be little affected by one dry summer. In Asia, these advantages are pronounced. In many Asian countries the hot season lasts as long as nine months and dries up many surface water supplies. During the three-month monsoon, in contrast, rainfall is often so heavy that water courses are turned into turbulent mixtures of mud and water.

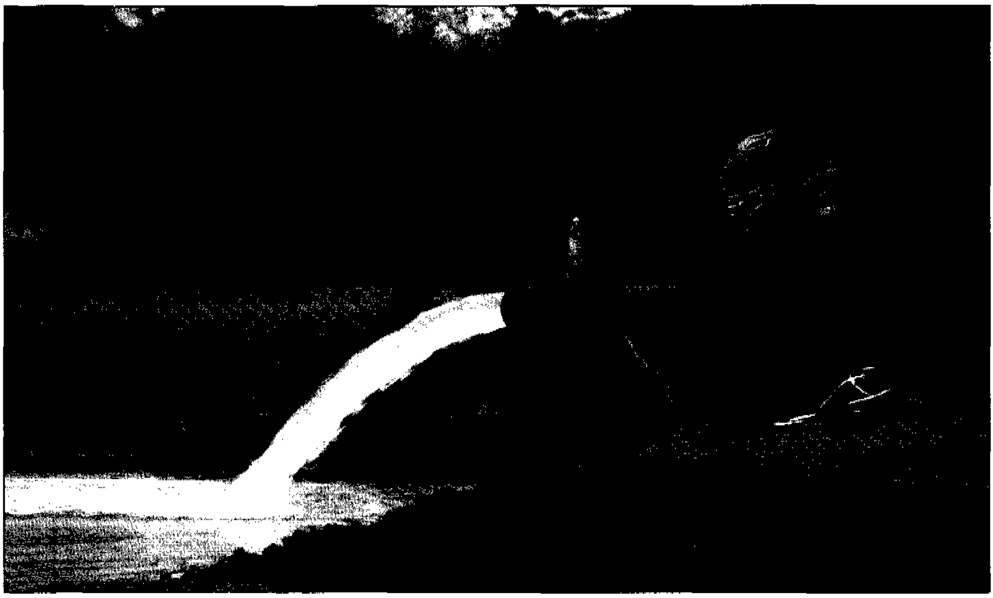
Secondly, as has been mentioned, groundwater is cheap to develop. This is partly because, if it is unpolluted, it requires little or no treatment before use and partly because it can be developed stage by stage. Whereas the development of surface reservoirs involves the construction of large and costly dams and reservoirs, groundwater can be developed as and when needed through the addition of boreholes and wells.

Thirdly, groundwater can often be tapped near to where it is needed while surface water must either be developed at the sites of natural dams or reservoirs, or piped considerable distances to where it will eventually be used.

However, groundwater is not just an alternative to the use of surface water. In many areas, it is groundwater that makes the use of surface water sources possible during dry seasons. Groundwater provides

Groundwater in the United States: key facts

- Groundwater resources under the United States are estimated at 125 000 km^3, roughly the equivalent of the flow of the Mississippi River for 200 years.
- Groundwater supplies more than half of US drinking water, and 96 percent of the drinking water consumed in rural areas.
- Some 30 percent of the groundwater used in the United States for irrigation comes from one aquifer—the Ogollala running from Dakota to Texas.
- Dams along canals in southern Florida are needed to prevent saltwater contaminating the Biscayne aquifer which supplies drinking water to 3.5 million Floridians.
- Groundwater abstractions have lowered the ground by up to 3 metres in the Houston-Galveston area, giving rise to coastal and inland flooding. Land in California's San Joaquin Valley has sunk by as much as 8 metres since the 1920s.
- Over-abstraction caused water levels in the Northern Midwest aquifer system to fall by more than 300 metres. Many Chicago suburbs switched to water from Lake Michigan and the water table has now risen by 75 metres since 1985.
- Radioactive waste from a former nuclear production facility near Richland, Washington, has contaminated parts of the aquifer below.
- Some three million people are supplied from a three-tiered aquifer below Long Island—but the top tier of the aquifer is now contaminated by oil and gasoline, septic tank effluents and pesticides.



Jeff Davies/British Geological Survey

High-yielding boreholes are widely used for irrigation and urban water supply.

the baseflow to many of the world's rivers, and this flow continues throughout the year, regardless of weather conditions. Many of the world's rivers would dry up in hot and dry summers were they not fed by groundwater. In this, groundwater resembles glaciers which are also an important source of river flow near mountainous areas during hot summers—the hotter the summer, in fact, the greater the flow provided by glaciers.

Finally, groundwater resources are also strategic resources in that they are often unaffected by catastrophic events such as earthquakes, volcanic eruption and war. While catastrophes of this kind can have long-lasting and serious consequences for surface water supplies, groundwater is rarely affected—though the poisoning of wells was an important part of medieval warfare in Europe.

How aquifers respond to drought

Aquifers can store considerable volumes of groundwater and, where the water table is deeper than 3 metres, evaporation losses from this stored water are negligible. For these reasons, groundwater is less affected by drought than surface water.

However, not all aquifers are insensitive to drought; those with limited groundwater storage can be susceptible to extended dry periods, particularly in semi-arid and arid regions where a relatively small change in the rainfall pattern can cause a disproportionate reduction in infiltration. This is because a considerable volume of water may be needed to satisfy the moisture deficit in the soil before deep infiltration to groundwater can occur.

In some areas of Africa and south Asia, a succession of years of below-average rainfall has caused severe water shortages. The effect of these extended dry periods on groundwater levels may be worsened if excessive groundwater abstraction depletes aquifer storage further.

The Deccan basalts of central India are particularly susceptible to drought. Less than 20 metres below ground surface, these aquifers store the equivalent of only 1–2 years of current abstraction. In the state of Maharashtra, groundwater pumping has increased more than six-fold in recent years. As a result, there appears to be a long-term decline in the water table, at least in some areas, and this has resulted in water levels approaching the base of the aquifer at the end of the dry season. Failure of the monsoon causes many of the irrigation wells in these areas to dry up completely and leads to serious crop losses. In some villages, even the community drinking-water wells become dry and expensive, emergency drilling programmes and water-tankering schemes have to be introduced.

Groundwater quality

Most groundwater originates from water that has permeated first the soil and then the rock below it. The soil removes many impurities and the rock through which the water then flows, perhaps for thousands of years, filters and purifies the water even further. It therefore usually reappears at the Earth's surface free of pathogenic micro-organisms—hence the strong and rising demand for bottled 'source' water (see box below). The fact that most groundwater needs no treatment before it is put to human use means also that groundwater is a cheap source of water. While this is advantageous, it also increases the risk that groundwater reserves become over-exploited. While groundwater is less easily polluted than streams and rivers, it often contains high concentrations of dissolved solids from the rock through which it has passed. As Pliny put it some 19 centuries ago, 'Water takes on the properties of the rocks through which it has passed'.

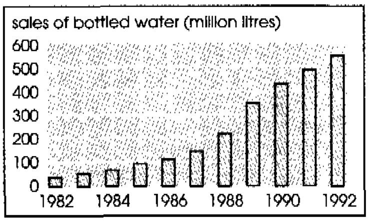
Bottled water: a fashionable resource?

Bottled water, obtained from springs and boreholes, often in mountain areas, has long been drunk in countries where the quality of rural or urban water supplies is suspect. As rivers and reservoirs have become increasingly polluted, and water treatment needs have increased, many households have turned to bottled water to avoid the increasingly unattractive taste of tap water.

In the United Kingdom, for example, the consumption of bottled water reached 500 million litres by the end of 1992. However, it was still only one-tenth the consumption in Belgium, France and Italy where average consumption is 100 litres per person per year. Bottled water typically costs 500 to 1000 times more than tap water, and—in restaurants, at least—is more expensive than petrol or even wine served by the carafe.

In the United States, as much as half of the bottled water that is drunk is purified mains water, known as 'designer water'.

While many people drink bottled water because they believe it to be healthier than mains water, tests have shown that many bottled waters have a low mineral content. According to a report in the UK journal *Which*, 'most still waters contain high levels of bacteria'—although most, if not all, of these are likely to be harmless.



Rise in sales of bottled water in the United Kingdom, 1982–92.

When groundwater is polluted, many processes occur during the water's long journey from the surface to a borehole in the aquifer which help attenuate contamination. Not only do contaminants become diluted but they can be absorbed by the rock itself and, in some cases, biochemically transformed into other compounds that are often less harmful than the original contaminants.

However, should groundwater become severely polluted—by industry, by landfills or by agricultural discharges, for example—the damage can be severe and very long lasting. Once pollutants reach the water table, it may take a very long time to flush out the aquifer completely. Furthermore, pollution can take a very long time to show itself since the water within aquifers moves so slowly.

Worse still, some industrial pollutants are relatively insoluble and heavier than water. They therefore sink to the bottom of an aquifer where they are slowly dissolved and dispersed into deep circulating groundwater over a period of many years. Once polluted, aquifers are difficult—indeed, sometimes impossible—to clean up. The process has been likened to trying to squeeze out the last traces of soap from a sponge.

Groundwater pollution, which is nearly always persistent and often irreversible, is becoming increasingly serious in many areas of the world.

The deterioration of groundwater

In many areas of the world, groundwater sources are under threat from human activities. These threats takes two main forms: the inadequate control of groundwater abstraction, resulting usually in some form of of over-exploitation; and the pollution of groundwater resources, usually by cities, industry or agriculture.

Both threats can result in either reversible or irreversible damage. In the first case, matters can be corrected and only the question of costs is involved. In the second case, costs are also involved but, in addition, sustainability issues arise since future generations are deprived of an important resource.

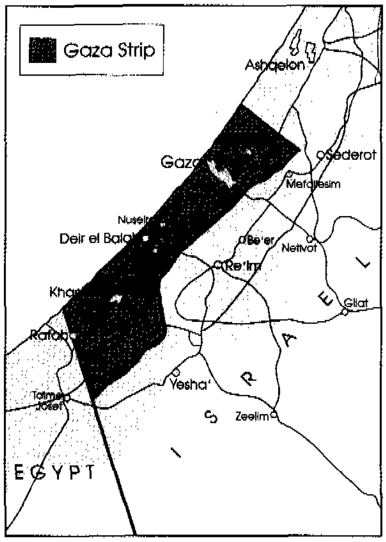
Inadequate control

Many aquifers are being over-exploited in the sense that water is being abstracted from them faster than the average rate of recharge. This leads to a reduction in groundwater in permanent storage and is sometimes called groundwater mining. Development of this kind is unsustainable and deprives future generations of a resource which is being used up by this generation.

In some countries, fossil groundwaters are being deliberately mined in attempts to speed the rate of development or reduce the cost of food imports. The mining of the sub-Saharan aquifer by Libya is one example (see box on page 8). A similar

Over-abstraction: the case of the Gaza strip

The shallow, sandy coastal aquifer that underlies the Gaza Strip is heavily over-pumped and becoming polluted. The Strip currently supports 800 000 people and a serious pollution risk is posed by the indiscriminate disposal of liquid and solid wastes. The aquifer is essentially the only source of water. The natural replenishment rate of the aquifer is estimated at 50–65 million m^3 a year. Abstraction rates are estimated at 80–130 million m^3 a year, of which most is used in inefficient forms of irrigation. Over-abstraction is causing saline intrusion, and irrigation with this water is causing soil salinization. Most of the population is not connected to mains sewerage and uses latrines draining to cesspits, many of which overflow into surface drains. Faecal contamination of groundwater is widespread and nitrate concentrations in some parts of the aquifer are reported to be 10 times the WHO guideline. Pesticide levels are also believed to be high and there is indiscriminate dumping of solid wastes throughout the area. Groundwater is no longer potable in some central areas, and Israel is transporting 5 million m^3 of drinking water into the Gaza area every year.



approach is being taken by Saudi Arabia which uses fossil groundwater to supply some 75 percent of its needs. Groundwater abstraction averages more than 5000 million m^3 a year, much of it used for the irrigation of wheat, in which the country became self-sufficient in 1984.

However, in many cases groundwater mining is more difficult to define than might at first appear. The recharge rate of groundwater resources is not a constant and can vary substantially with the rainfall pattern. What may be over-exploitation in one year may be a perfectly acceptable rate of exploitation in another. To complicate matters, in some arid areas major recharge occurs only once a decade or even less frequently. Defining a sustainable abstraction rate in such a situation is difficult. Nor are sustainable abstraction rates themselves constant. Climates are undergoing constant change, and these changes are reflected in the dynamic balances of groundwater resources. Furthermore, if global warming becomes a reality, the climatic changes that result will have a major impact on groundwater resources. Infiltration rates to these resources are likely to be substantially modified in some area of the world.

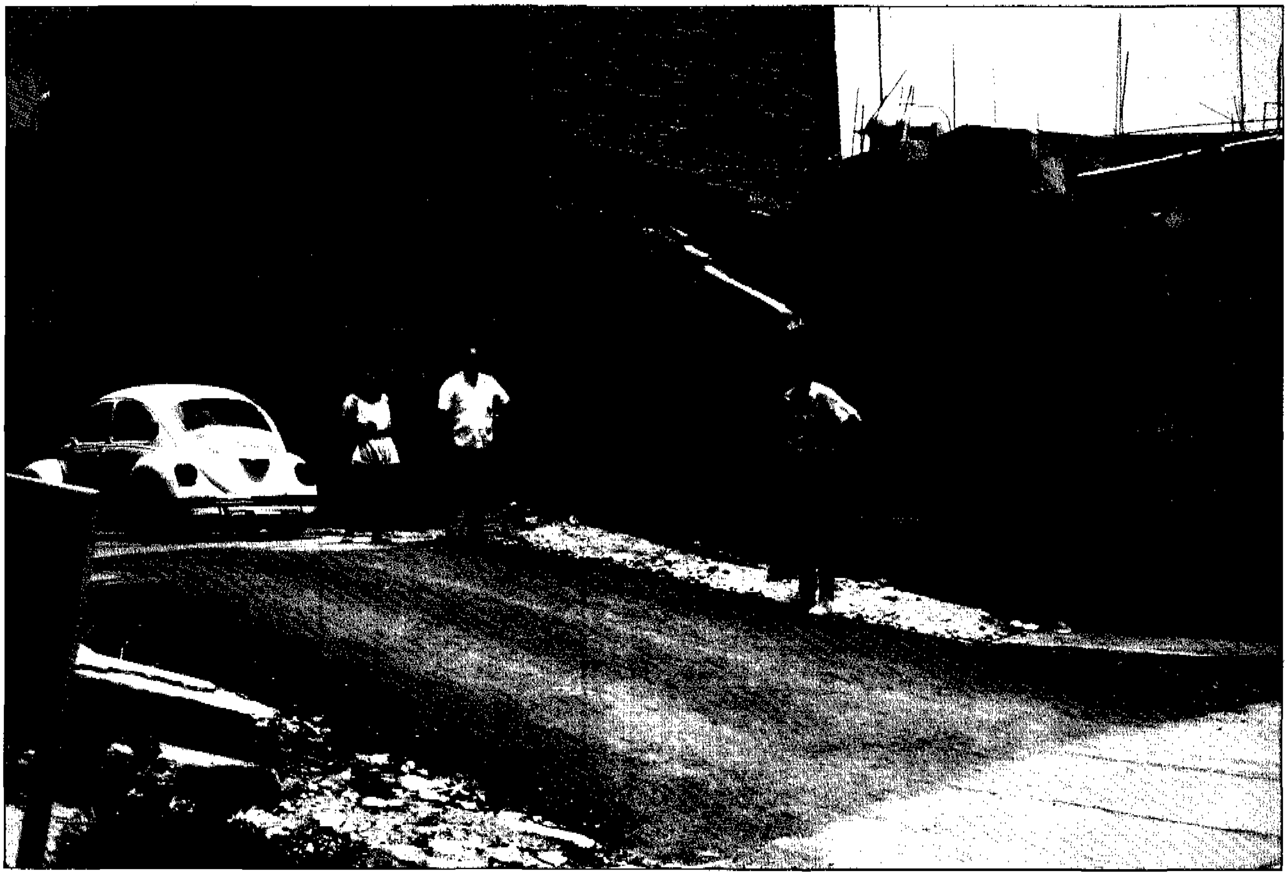
Even when recharge to groundwater exceeds levels of overall abstraction from the aquifer, groundwater development can have a number of negative consequences. The uncontrolled drilling of boreholes, for example, can lead to severe losses of yield and uneconomic production in some places. The lowering of water levels by borehole

Social equity and groundwater

The kinds of equity issue raised by shortages and pollution of groundwater are exemplified by the situation in the state of Gujarat in northern India. Water there is in short supply, particularly in the north where it rains on only a few days a year and where half the annual rainfall can occur over a period of two to three hours during the monsoon. Inevitably, groundwater supplies most domestic water and more than three-quarters of irrigation water.

Over-abstraction has caused the water table to fall, in some places by as much as 40 metres. This has deprived many poor farmers of water since they can afford only dug wells, which are often limited to depths of 10 metres or so by wall instability. Only richer farmers can afford the US$13 000–14 000 required to sink boreholes down to the 400-metre depths that may be required. Elsewhere over-abstraction has caused saline intrusion and richer farmers have responded by buying land further inland, pumping uncontaminated water from it and piping the water to their fields.

Many management plans to deal with over-abstraction have worsened equity problems. For example, attempts to control over-abstraction have involved refusing credit and the supply of electric power for pumping for new wells and boreholes in areas where extraction rates exceeds 65 percent of recharge. Some rich farmers continue to develop the groundwater resource, and avoid these restrictions by financing new developments themselves and obtaining electric power illegally. Equity issues are accentuated by the fact that the poor have little representation in the government organizations that develop groundwater policies. Attempts to manage groundwater resources sustainably may worsen equity issues: limiting access to groundwater under these circumstances may result in the allocation, by default, of the bulk of the resource to wealthy sections of society.


Stephen Foster/British Geological Survey

Land subsidence caused by a falling water table in a Mexican city.

abstraction can reduce spring flow; these springs may be essential for water supplies or for maintaining wetland habitats.

Problems of social equity

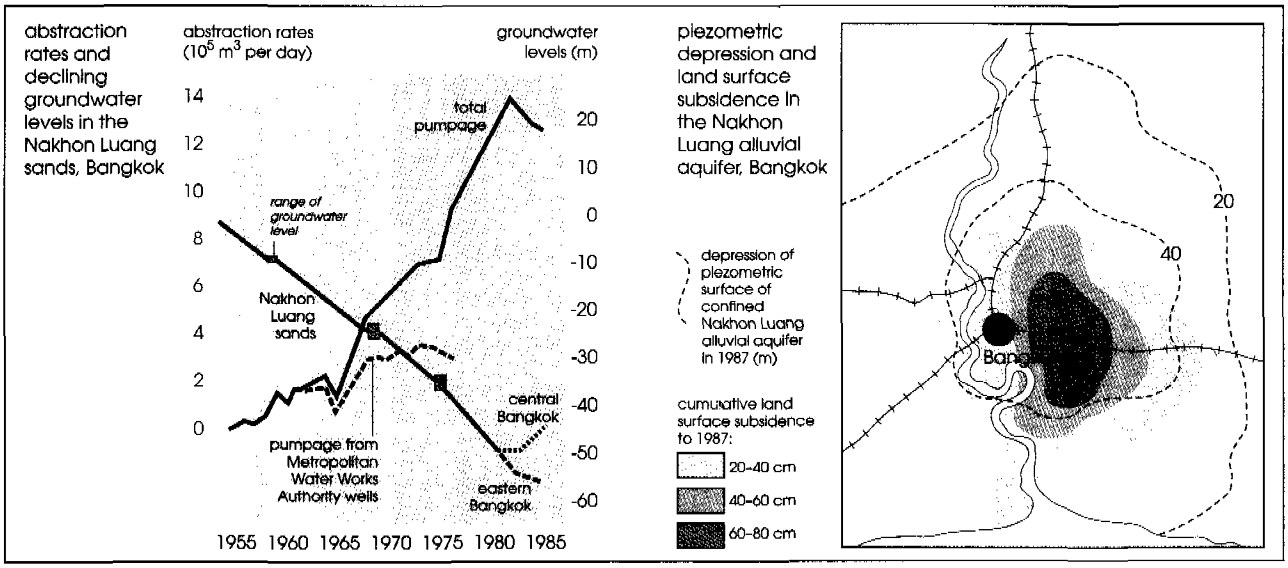
Groundwater (like fish stocks) is a resource whose legal ownership is difficult to define. It is often regarded as a common property and, like many resources of this kind, users can benefit from the resource while not themselves suffering from the results of their own actions. They can, for example, continue to draw water while diminishing or polluting the supply for others. Conversely, they may be deprived of the resource through the action of others. Furthermore, the cause and effect chain is difficult to establish for degraded aquifers, making it difficult to apply the well established 'polluter-pays' principle.

The effects of falling water tables

Over-abstraction leads to physical as well as social problems in some areas. The water table has fallen so low under parts of Mexico City, for example, that there has been widespread ground subsidence, involving costly rebuilding. Subsidence is caused by water draining from the pores in underground strata, causing the rock to compact. Unconsolidated strata, especially clays which have a high water content, are particularly susceptible.

Parts of the Las Vegas valley in the United States have fallen by more than 1.5 metres as a result of over-abstraction in an area where annual rainfall averages only 100 mm. Arizona is marked by a series of hundreds of fissures in the ground, caused by over-abstraction, which have disrupted roads, railways and housing.

Such problems are neither confined to arid countries nor to developed ones. Bangkok is suffering from acute water problems as a result of the over-exploitation of the water table beneath the city. In Beijing recently, over-abstraction caused the water table to drop by more than four metres in a year. According to the Chinese National Environment



Abstraction rates and land subsidence in Bangkok, Thailand.

Protection Agency, as many as 45 Chinese cities are now experiencing some form of land subsidence as a result of the over-abstraction of groundwater.

In the United States, according to one estimate, 21 percent of irrigated land is now fed from groundwater resources that are being depleted faster than they are replenished. The problem is the most severe in the arid south-west where cities from Utah and Colorado to Nevada and New Mexico are being forced to buy farmland in order to acquire the rights to use the groundwater that lies under the land. In 1987, for example, Phoenix, in Arizona, bought nearly six million hectares of farmland for US$29 million to help satisfy its citizens' demand for water.

In many countries, competition for groundwater is forcing cities to obtain additional supplies from surface water sources some distance away. Inevitably, water costs then increase.

Saltwater intrusion

Under natural conditions, coastal aquifers discharge freshwater into the sea. Where substantial volumes of groundwater are abstracted, however, this process may become reversed, with salt water moving inland and polluting the aquifer. Salt water intrusion has occurred in many places of the world including India, China, Mexico and the Philippines. The problem is particularly severe under Metropolitan Manila, where groundwater abstraction has lowered the water level by 50–80 metres. As a result, salt water has seeped into the Guadalupe aquifer that lies under the city, reaching as far as 5 km inland. The situation is even worse north of Madras in India where salt water intrusion has moved as much as 10 km inland, causing many irrigation wells to be abandoned. Chloride concentrations in parts of the aquifer that lies under Bangkok—where the water level has dropped by up to 60 metres—have risen from 10 mg/litre to more than 600 mg/litre. Here the salt comes not from the sea but from saline fossil water trapped deep in the aquifer. Increasing salinity has caused many tubewells to be abandoned.

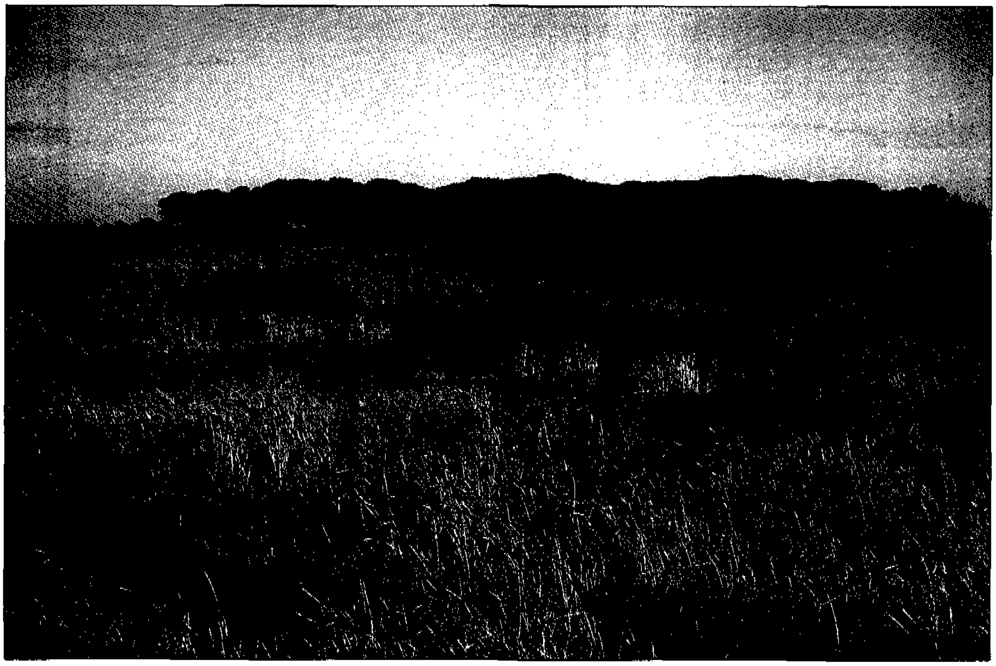
Salt water intrusion is a particularly serious problem on small ocean islands such as the Maldives. On many of these islands, the freshwater aquifer is only a few metres thick and is surrounded by salt water. Furthermore, groundwater is the only reliable source of freshwater. For these reasons, aquifer abstraction has to be well managed.

The threat to wetlands

As water tables fall, groundwater discharge reduces or ceases and the land dries out. This can have serious effects on wetlands, one of the few remaining ecosystems still to support large numbers of plant and animal species not found elsewhere.

A number of the world's major wetland areas are now under threat from the over-abstraction of groundwater. The threat is not only to the habitat of many rare species of plants and animals. Wetlands also play important roles in purifying the water supplies of inland lakes, and their removal often leads to serious problems.

The Coto Doñana National Park in southern Spain occupies an area of 85 000 hectares and is fed by the River Guadalquivir. It is one of the most important wetlands in Western Europe for the conservation of biological diversity. As demand for groundwater has increased from tourism development and for horticulture—mainly to grow


J. Plant/WWF

Natural wetlands are home to many plant and animal species, and act as natural purification systems for lakes downstream. Many are threatened by over-abstraction of groundwater resources.

strawberries in March for export to north Europe—the freshwater aquifer that feeds the marshes has become seriously depleted, leading to a risk of saline incursion and a shortage of freshwater.

This is not an isolated case, and there is an urgent to protect other threatened wetlands in the Mediterranean basin, in particular in Algeria, Cyprus, Tunisia, Egypt and Turkey. In all these countries, increasing salinity and changing water levels are leading to vegetation changes in important wetlands.

The effects of rising water tables

Conversely, some forms of development result in rising water tables. This occurs commonly on over-irrigated land and can lead to substantial losses of agricultural production. One result is

The fall and rise of the city water table

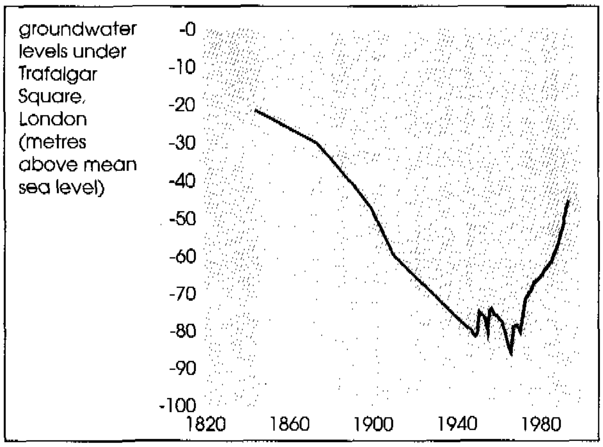
Urbanization, and the heavy demand for water that accompanies it, has resulted in falling water tables under many of the world's cities, leading to reduced yields, the threat of saline encroachment and land subsidence.

Abstraction by wells and boreholes from shallow aquifers under cities causes a 'cone of depression' in the aquifer. Where this occurs in a coastal aquifer, seawater may move inland and contaminate the aquifer. Seawater intrusion has occurred over distances of several kilometres beneath Manila and Cebu City in the Philippines and Jakarta in Indonesia.

Excessive groundwater abstraction may also induce upward movement of saline water, trapped within sediments at depth. This has happened in Bangkok where pumping has lowered the water level in the most important confined aquifer by more than 60 metres.

These problems have led to decreasing dependence on groundwater for some cities and the importation of surface water over long distances.

Similar declines in water tables have been found under cities in industrialized countries. Water levels under London, Liverpool and Birmingham in the United Kingdom, for example, declined by up to 30 metres during the first half of the 20th century. Since then, however, the water table has begun to rise again as heavy industry has either closed down or has moved away from city centres. Water levels are now rising towards those prevailing at the beginning of the century, raising fears about future flooding of basements and tunnels, and damage to foundations. In Liverpool a British Rail tunnel has also flooded, and two large pumping stations on either side of the Mersey estuary have to be operated to keep railway tunnels from flooding. In London the water level rise is currently more than two metres a year; since the Chalk under London is confined by a deep clay layer, there are fears that rising water pressure could lead to expensive damage to the foundations of many London buildings.



The area of land being abandoned each year as a result of salinization and waterlogging is now roughly equal to the amount of land being reclaimed and irrigated.

waterlogging of agricultural land, which makes land impossible to till and thus effectively puts it out of agricultural production. Waterlogging is often associated with salinization, which has two causes: a rising water table that brings saline water into contact with plant roots; and the evaporation of irrigation water by the sun, leaving the salts behind. In the mid-1970s, the United Nations Food and Agriculture Organization estimated that 952 million hectares of agricultural land were affected by salt. The area of land being abandoned each year as a result of salinization and waterlogging is now roughly equal to the amount of land being reclaimed and irrigated (see box below).

Water tables are also rising under some of the world's major post-industrial cities. This results from the fact, already mentioned, that urban recharge rates may be higher than natural, pre-urban ones. While this was of little import when cities were also industrial centres, consuming large quantities of water, in many developed countries the city and heavy industry have now been divorced, with industry either closing down or being moved to less urban areas. In addition, groundwater abstraction rates within urban areas have declined dramatically because public water supplies are now mostly obtained from outside the city (to avoid potential problems of contaminated groundwater). The rise in the water table that then results can become an expensive embarrassment in cities where, for example, large underground car parks exist, which then have to be regularly pumped dry—or put out of action.

Salinity and irrigation

The UN Food and Agriculture Organization estimates that of the 237 million ha currently irrigated, about 30 million ha are severely affected by salinity and an additional 60–80 million ha are affected to some extent. UNEP recently reported that the rate of loss of irrigated land from waterlogging and salinity is 1.5 million ha per year. Millions of hectares of irrigated land, from Morocco to Bangladesh and from northwestern China to central Asia, suffer from this condition. Salinity-affected areas as a percentage of total irrigated area is estimated to be 10 percent in Mexico, 11 percent in India, 21 percent in Pakistan, 23 percent in China and 28 percent in the United States.

Salinity is caused by a combination of poor drainage and high evaporation rates which concentrate salts on irrigated land; it mainly occurs in arid and semi-arid regions. All irrigation water contains some salt and can leave behind tonnes of salt per hectare each year. Unless this salt is washed down below the root level, soil salinity will result.

A related concern is the rapid rise in groundwater levels, leading to waterlogging and depressed crop yields. Waterlogging is not an inevitable result of irrigation. It occurs when excessive water is used in systems with finite natural drainage.

At the end of the 1950s, Pakistan began to sink wells to pump out salt-laden water. The initial capital costs were high and operating costs have been increasing constantly. Today, Pakistan spends more money on reclaiming land than on irrigation.

Source: The State of Food and Agriculture, FAO, 1993, p. 289

The pollution of groundwater

Restoration of a seriously contaminated aquifer to drinking water standards is always costly and often impossible.

Once polluted, groundwater is extremely difficult to purify on account of its inaccessibility, its huge volume and its slow flow rates. Unfortunately, the world's aquifers are becoming increasingly polluted as a result of human action. Three effects will be examined in more detail in the pages that follow: pollution resulting from urbanization, from industrial activity and from agriculture. All are serious.

Some of the contaminants found in groundwater are listed in the table on the right, which also shows World Health Organization drinking water quality guidelines. In parts of many aquifers, some of these values are exceeded, particularly that for nitrate which is an increasingly widespread pollutant resulting from inadequate sewerage treatment and intensive agricultural cultivation. Restoration of a seriously contaminated

WHO drinking water quality guidelines (1984, mg/litre)

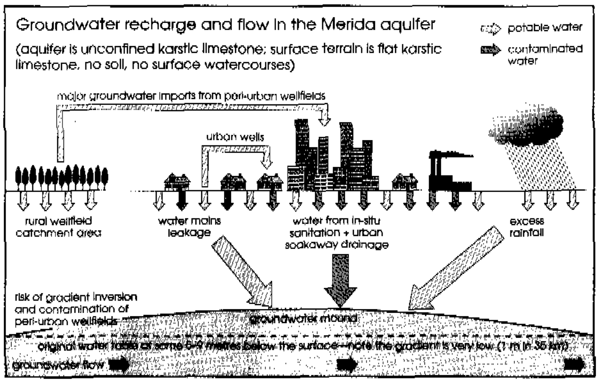
aluminium (Al)	0.2
arsenic (As)	0.05
chloride (Cl)	250
chromium (Cr)	0.05
cyanide (CN)	0.1
fluoride (F)	1.5
iron (Fe)	0.3
lead (Pb)	0.05
manganese (Mn)	0.1
nitrate (NO_3-N)	10
sodium (Na)	200
sulphate (SO_4)	400
2,4-D	0.1
benzene	0.01
carbon tetrachloride	0.003
chloroform	0.03
DDT	0.001
tetrachloroethene	0.01
faecal coliforms (/100 ml)	nil

The impact of urbanization of groundwater in Merida, Mexico

Merida, a city of 535 000 inhabitants located on the Yucatan Peninsula of Mexico, is underlain by a highly permeable limestone from which it obtains all its water supply of 240 million litres a day. Most of this is imported from wells outside the city limits.

There is no mains sewerage system nor piped stormwater drainage, all wastewater being returned to the ground via on-site sanitation units and all surface drainage via soakaways. Because of this, and the high water consumption per capita (460 litres a day), urban recharge is very high (600 mm a year) and substantially greater than the pre-urban background infiltration to groundwater of 100 mm a year.

The water table is some 5–9 metres below the ground surface and is of very low gradient (1 m in 35 km). The shallow groundwater immediately beneath the city is seriously contaminated by faecal coliforms and nitrate is kept partly in check only by the dilution provided by the increased recharge and high throughflow. There is concern that this polluted water could eventually migrate to the wellfields outside the city which supply Merida.



Groundwater recharge and flow in the Merida aquifer

(aquifer is unconfined karstic limestone; surface terrain is flat karstic limestone, no soil, no surface watercourses) aquifer to these drinking water standards is always costly and often impossible.

The effects of urbanization

Urbanization introduces many changes to the aquifers that lie under cities. Natural recharge mechanisms are modified or replaced and new ones introduced. Leakages and seepages from mains water and sanitation systems become an important part of the hydrological cycle in the urban environment.

Many sub-city aquifers in the developing world, where few of the urban population are connected to mains sewerage, are polluted with human wastes. Septic tanks, cesspits and latrines are common in all major cities in developing countries. Septic tanks, when properly operated, produce an effluent of acceptable quality in areas of low population density. In practice, however, they are often overloaded and operate inefficiently. Effluent is often discharged directly into inland waterways, whence pollutants find their way into the underlying aquifer. In cities such as Jakarta and Metro Manila, which have 900 000 and 600 000 septic tanks respectively, the ensuing pollution is serious.

Other forms of excreta disposal can be even more dangerous since they often drain directly into the ground, carrying with them pathogens responsible for many human diseases. Since in many cities drinking water is provided by shallow private boreholes, many of which are inadequately protected from pollutants, bacteriological quality can be poor. A study in Sri Lanka has shown that water from a latrine soakaway in a suburb of Kandy entered a borehole 25 metres away within two or three days—insufficient time to attenuate or eliminate any pathogens.

Pathogens in groundwater

Four types of pathogen are found in human excreta: helminths, protozoa, bacteria and viruses. Under favourable conditions, pathogens are large enough to be filtered out of water passing through the soil and the unsaturated layer but bacteria and viruses, and occasionally protozoa, can sometimes be transported into groundwater.

Most pathogens do not survive long in groundwater: at 20 °C, a 90 percent reduction usually occurs within about 10 days. However, some species may survive for 200 days or more as a result of the absence of ultraviolet light, lower temperature and less competition for nutrients.

Overall, however, filtration, die-off and aquifer dilution normally reduce numbers to acceptable levels well within 50 days. For granular aquifers, where travel times to the water table and water movement are slow, this is long enough to protect the water in wells. However, the rapid transport that occurs in fractured rocks can carry large number of pathogens into wells.

Surveys of groundwater quality in four Indian cities (Madras, Hyderabad, Nagpur and Lucknow) which are largely unsewered show that there is widespread contamination of shallow groundwater by nitrate, with nitrate concentrations well above the WHO drinking water guideline of 10 mgN/litre. Nitrate concentrations in the groundwater beneath Beijing exceed the WHO guideline over an area of more than 20 km^2.

In Sri Lanka, the water supply for the city of Jaffna comes entirely from groundwater. The urban population of 150 000 is virtually unsewered and domestic effluents are discharged to the ground via septic tanks and latrines. Partly as a result of this, the aquifer is contaminated; nitrate concentrations are double the WHO guideline in many places and in some they reach values of five times the guideline.

In many cities in developing countries—particularly where the monsoon brings the water table to the surface and disposal of sanitation wastes to the ground is not possible—human faeces and other wastes are discharged directly into streams, canals and rivers. Heavy loads of untreated effluent exceed the natural purification capacity of these watercourses for many kilometres downstream. In many areas, on-site sanitation systems also lead to increases in organic carbon concentrations and reduced oxygen concentrations. This, in turn, can lead to the production of more soluble iron compounds, resulting in unacceptably high levels of iron in the groundwater. Sulphate, derived largely from detergents, may also be high.

Wastewater discharge and reuse

While sewage and wastewater from cities is normally regarded as a major source of pollution, it is really a large and important resource. In some arid areas, it is used, with minimal, if any, treatment to irrigate crops, including some intended for direct human consumption. The water used also supplies crops with essential elements such as nitrogen and phosphate which would otherwise have to be added as artificial fertilizer.

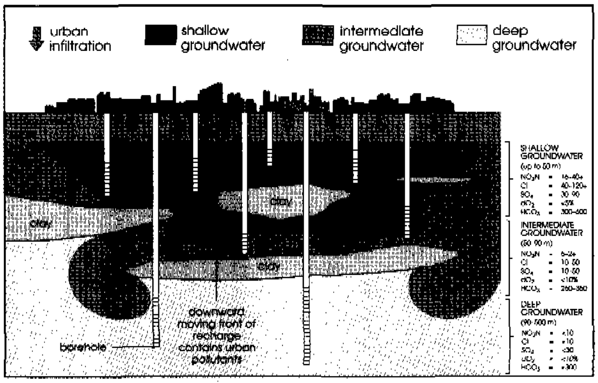
There is debate about the safety of this procedure and some experts believe that a

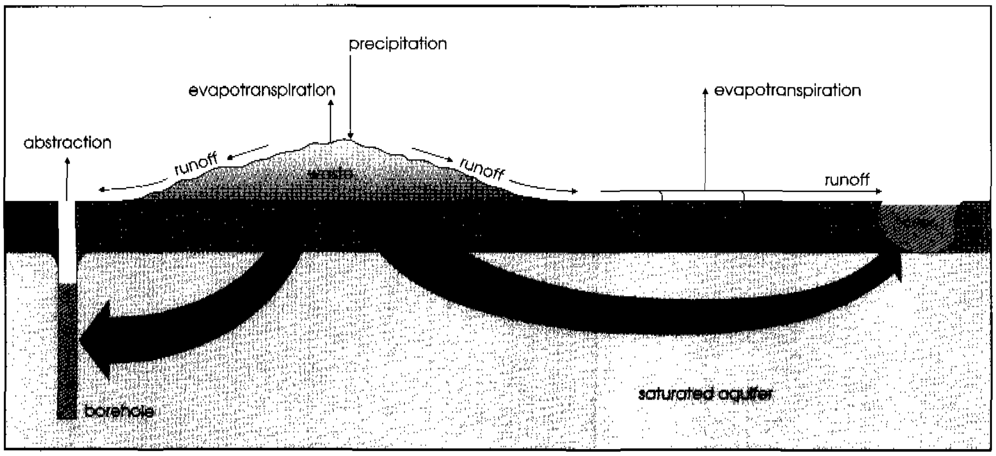
Incipient contamination of deep groundwater under Santa Cruz

The city of Santa Cruz, located on plains to the east of the Andes in Bolivia, obtains all its water from a deep semi-unconfined aquifer system below the city. The city is largely unsewered and most of the wastewater is discharged to the ground. Groundwater in the deeper aquifer below 100 metres is of high quality. However, at depths of less than 45 metres there are high nitrate and chloride concentrations, typically in the range 10–40 mgN / litre and 40–120 mg / litre respectively, beneath the more densely populated districts. Bicarbonate and manganese concentrations are also raised and dissolved oxygen levels reduced.

The nitrate and chloride is believed to come from unsewered sanitation. Oxidation of organic wastes in the shallower groundwaters consumes the available dissolved oxygen and produces carbon dioxide, which in turn reacts with carbonate minerals in the aquifer matrix to produce bicarbonate. Manganese, which occurs naturally in the aquifer matrix, is dissolved in the reducing conditions thus produced. The higher sulphate concentrations also found in the shallow groundwater are thought to be partly derived from detergents and highway runoff.

Concentrations of these pollutants in water at depths of 45–100 metres have begun to increase, though less so than in the shallow aquifer. Downwards leakage from the shallow aquifer as a result of groundwater abstraction from depth is thought to be the cause of this increase in concentration.





Flow paths of contaminants from a waste disposal site.

better use for urban wastewater is probably to recharge the aquifer from which it came. During the recharge process, the water is considerably purified. If it is required for irrigation, it can then be abstracted either from irrigation wells or from streams whose flow has been increased by the recharge.

Letting sewage water stand in shallow surface ponds and filter down through the soil and the aquifer below can be an effective means of treatment. The more slowly this is done, and the more that the surface ponds are rested between treatments, the more complete will be the treatment. Allowing the ponds to dry out regularly encourages the breakdown of nitrates in the sewage, with the release of harmless nitrogen gas. With careful control nitrogen concentrations in the recharge water can be reduced to below 5 mg/litre. At the same time, most bacteria and protozoa are eliminated, and levels of organic compounds and phosphates are greatly reduced. Although the technique is expensive in terms of land area used because the surface ponds should be allowed to dry out for periods that are twice as long as the period for which they are used, infiltration treatment has the added advantage of providing a cheap underground storage system from which water can be pumped for non-potable uses.

Solid waste disposal

Large volumes of solid wastes are produced and disposed of in all major cities. In China alone, the domestic refuse from 370 cities exceeds 60 million tonnes a year. Disposing of these wastes can give rise to serious groundwater pollution. The worst risks occur where uncontrolled tipping, as opposed to controlled sanitary landfill, is practised, and where hazardous industrial wastes, including drums of liquid effluents, are disposed of at inappropriate sites which are selected on the basis of their proximity to where the waste is generated rather than their suitability as landfill sites.

Often no record is kept of the nature and quantity of wastes disposed of at a given site and abandoned sites represent a potential hazard to groundwater for decades. To make matters worse, disposal is often on low ground where the water table is high and direct contamination of shallow groundwater likely. In a study made of six solid waste tips in Jaipur, India, it was found that water quality was clearly correlated with distance from the tips. Wells even 450 metres away had high levels of chloride, sulphate, bicarbonate and ammonia, even though the tips had been in use for only 12 years. In a study of selected landfill sites in the Bandung area of Indonesia, all sites were found to generate a leachate containing high quantities of chloride, sodium, calcium, bicarbonate, boron and various organic compounds. At one site pollution from the landfill was detected in a well 120 metres away.

A further complication in developing countries is that urban expansion may eventually lead to the erection of marginal housing on areas previously used for solid

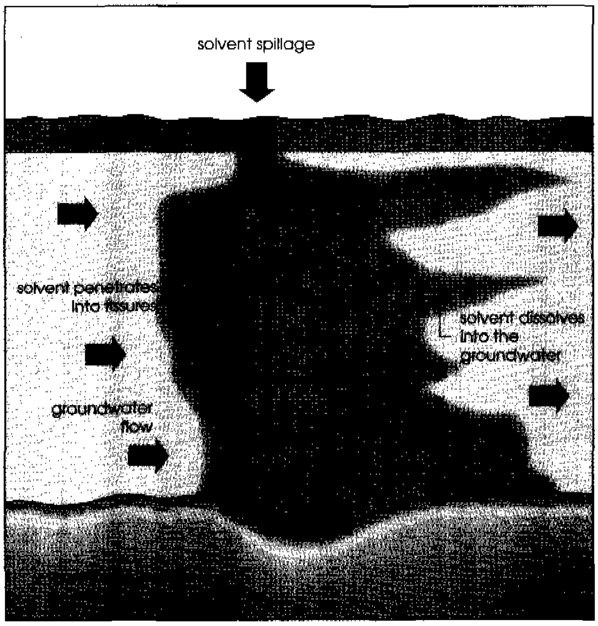
Groundwater pollution from industrial solvents

Before their damaging effects on the ozone layer were fully appreciated, chlorinated solvents were widely used as degreasers in the metal, paper, electronics and leather industries. These solvents are also insidious pollutants of groundwater because they have low solubility in water, and are denser and less viscous than water. This means that once they enter an aquifer they penetrate to great depths extremely quickly. They are also very resistant to biodegradation. In Europe there are many places, especially beneath cities and long-standing industrial sites, where chlorinated solvents are still present at concentrations many times the EC drinking water guideline value (less than 10 μg/litre) even 20 years after they entered the aquifer.

Research after a spill at a leather processing factory in Cambridgeshire showed that the pollutant had travelled down to a depth of some 50 metres and laterally by about 1 kilometre. How much of the chemical—perchloroethylene—was originally spilled is not known but sampling later suggested that 10–100 tonnes of the material could be in the aquifer.

'Pump and treat' is the name given to the most common means of restoring aquifers polluted in this way. The process involves pumping contaminated groundwater from close to the pollution source, treating the water and then returning it to the aquifer upstream from the site of pollution. This effectively contains the spread of pollution although restoration of the aquifer to a state even approaching its original pristine condition can take many years and cost millions of dollars. Complete restoration is often impossible.

Typical distribution of chlorinated solvent in a fractured porous aquifer after a major spill.



waste disposal. These settlements are rarely supplied with piped mains water and rely instead on privately-constructed shallow wells. These supplies are unmonitored and pose a serious threat to human health.

Pollution from industry

Nearly all industries produce liquid effluent. In the developed countries, strict legislation has ensured that much of this effluent is now properly treated before it is allowed to be discharged to a water course. This is not yet the case in many developing countries, where industries are commonly sited on the unsewered outskirts of towns and cities. The worst polluters are usually not the largest industries (which can normally afford some form of effluent treatment) but small industries producing paper and textiles, processing leather, metals and other materials, and repairing vehicles. These industries generate effluents containing spent acids, oils, fuels and solvents, many of which are discharged directly into the ground or nearby water courses, particularly canals. Small service industries—such as metal workshops, dry cleaners, photo processors and printers—also use considerable quantities of potentially toxic contaminants, and their disposal practices are often poorly controlled.

Chlorinated solvents are particularly insidious pollutants because of their persistency, toxicity and the way they travel in aquifers (see box opposite). A survey of 15 Japanese cities has shown that 30 percent of all groundwater supplies were contaminated by chlorinated solvents and in 3 percent of the samples taken concentrations exceeded WHO drinking water guidelines (30μg/litre). In some cases solvents were found in groundwater as far as 10 km from the site of the spill. A common cause of solvent pollution is leaking storage tanks and at one site groundwater beneath such tanks has been found to contain 40 000 μg/litre of the chlorinated solvent trichloroethene. Solvent contamination has in fact been found in almost all surveys of urban groundwater. Unfortunately, cleaning up a polluted aquifer—usually by removing contaminated soil and continuous pumping of the aquifer—is extremely difficult, very costly and takes a great deal of time. In 1982, some 50 m^3 of a chlorinated solvent leaked from a tank on the island of Puerto Rico. Five years later concentrations of the chemical in the aquifer below had been somewhat reduced but the cost of supplying alternative water sources had already exceeded US$10 million.

Industrial effluents also often contain high levels of metals such as iron, zinc, chromium and cadmium. Many are highly toxic, even carcinogenic, and even low concentrations in groundwater pose a serious threat to health. A study of metal contamination in Ludhiana, in the Indian Punjab, revealed high concentrations of heavy metals several kilometres from an industrial site where foundries and factories associated with electroplating and bicycle manufacture were discharging effluents directly into unlined channels and shallow soakaways. High concentrations of chromium and cyanide were found in shallow groundwater and copper and lead were also present.

Solvents and heavy metals are only two of the products of industrial activity. There are many others. A survey of industrial activity in São Paulo State in Brazil has attempted to categorize the groundwater pollution potential of 22 industries (see list right).

Groundwater pollution potential of industry types

Group 3:
high risk

- metal processing
- mechanical engineering
- petrol and gas refineries
- plastic products
- organic chemicals
- pharmaceuticals
- leather tanning
- pesticide manufacture
- electric and electronic manufacture

Group 2:
medium risk

- iron and steel
- non-ferrous metals
- rubber products
- inorganic chemicals
- pulp and paper
- soap and detergents
- textile mills
- fertilizers
- sugar and alcohol
- electric power production

Group 1:
low risk

- non-metallic minerals
- woodwork
- food and beverages

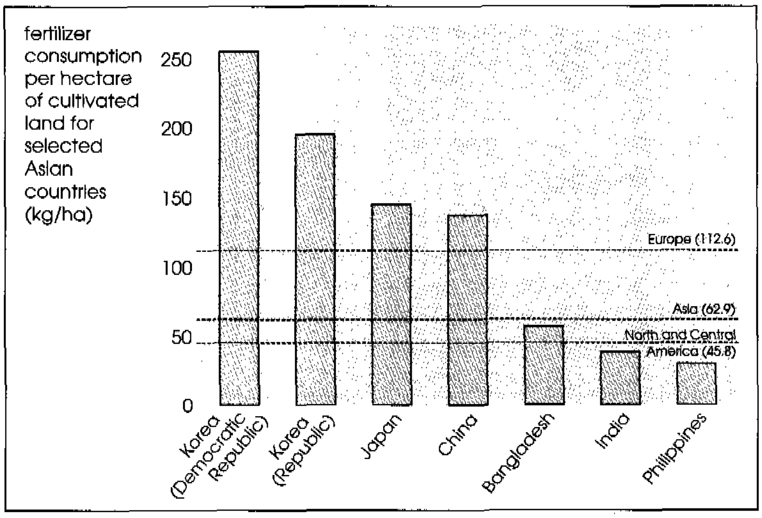
A study in Sri Lanka has shown that more than 60 percent of the applied nitrogen is lost ... producing groundwater concentrations of 20–50 mgN/litre.

Mining and petroleum development

Mining and petroleum extraction pose special risks to groundwater. Quarrying and open-cast mining, for example, remove the protective layer above an aquifer, leaving it more vulnerable to pollution. Deep mines or oil fields may produce fluids that are disposed of at the surface and may therefore contaminate shallow aquifers. And contaminants from spoil heaps may leach into groundwater.

Several serious cases of groundwater pollution are on record from these causes. In Zibo city in north-east China, petroleum wastes from a major petrochemical works have seeped into the ground and polluted groundwater over an area of more than 10 km^2. Both Australia and Canada have devoted considerable effort to trying to reduce leaching from spoil heaps, since the material that is leached away is often very acid and contains high concentrations of sulphate and toxic metals. In Thailand, a number of drinking wells have become contaminated with arsenic following leaching from the spoil from small-scale mining.

The graph below shows that fertilizer consumption in a number of Asian countries has now overtaken European and American levels.



Rising water levels in abandoned mines produce what is called acid mine drainage—the mobilization of oxidized metal ores which produce water rich in sulphate, iron, manganese and other metals. This can cause serious groundwater contamination.

Pollution from agriculture

Fertilizers and pesticides

Agriculture is responsible for the serious pollution of many of the world's aquifers. The main problem arises from the intensive use of nitrogen-rich fertilizers and of pesticides, a problem that has spread from the industrialized countries to developing ones, particularly those in Asia where the use of new, high-yielding crop varieties depends on the intensive application of fertilizer. In India, for example, fertilizer use has quadrupled over the past 20 years or so. In some Asian countries, fertilizer use has now overtaken that of Europe and the United States (see graph).

The high levels of nitrate and, in some areas, pesticides in groundwater have been identified as originating from intensive agriculture in a number of places. Pollution of groundwater is generally worse where the soil is very permeable, allowing agricultural chemicals to be quickly washed down to underlying aquifers. However, not all nitrate in groundwater is due to agriculture—much of it, as we have seen, also comes from untreated sewage. Monitoring techniques cannot differentiate between agricultural and sewage nitrate.

The leaching of nitrate from fields not only leads to pollution but is also a serious source of waste—nitrate that percolates down into aquifers has done nothing to stimulate plant growth. A study in Sri Lanka has shown that more than 60 percent of the applied nitrogen is lost in this way, producing groundwater concentrations of 20–50 mgN/litre. Elsewhere in Sri Lanka, a survey of the Jaffna Peninsula found that 79 percent of wells had concentrations of more than 11.3 mgN/litre and 48 percent greater than 22.6 mgN/litre. Other components of fertilizers, including potassium and chloride, also find their way from fields to aquifers.

More than 300 pesticides are currently in use. By definition they are designed to be toxic and, sometimes, persistent. Permitted concentrations in drinking water range from 0.1 to 100 parts per billion, and there is little doubt that pesticides do find their way into groundwater. However, the extent of pollution is not accurately known, even in Europe and the United States. Most observed concentrations have been in the range 0.1 to 100 μg/litre. One reason they are not higher is that the average half-life of a pesticide in the soil—normally less than 100 days—is relatively short compared to the rate at which they are leached through the soil and carried down to underlying aquifers.

One encouraging aspect for the future is that high levels of artificial fertilizer and pesticide application are not now seen as the principle means of developing sustainable agriculture. Instead the UN Food and Agriculture Organization is encouraging the use of Integrated Plant Nutrition (IPN) and Integrated Pest Management (IPM)—techniques that aim to promote plant growth through a variety of different techniques which are often cheaper and more effective than the application of chemicals alone.

Irrigation with groundwater. The high capital and operating costs of such intensive irrigation must be matched by heavy agrochemical inputs to ensure high productivity and good economic returns.

Salinity

Soil salinization and waterlogging have already been described on pages 20–21. They are caused not by pollution but by poor land management and the inadequate drainage of irrigated areas. The solution to these problems involves measures such as the lining of irrigation canals, introducing sprinklers or drip irrigation techniques, improving the flow of irrigation water and, in extreme cases, physically lowering the water table to 2–3 metres below the surface by pumping.

However, irrigation can also lead to the salinization of groundwater if excess irrigation water leaches out salts present in the soil and the unsaturated zone—particularly where rainfall is low and the salts have accumulated over thousands of years. This is a less common problem than soil salinization and its effects are not generally as serious. Careful control of the volumes of irrigation water used and the sites chosen for irrigation can reduce groundwater salinization.

Implications for policy

Although groundwater is one of the world's key natural resources, on which more than 1500 million people depend for drinking water, it is still undervalued, inefficiently exploited and inadequately protected.

Although groundwater is one of the world's key natural resources, on which more than 1500 million people depend for drinking water, it is still undervalued, inefficiently exploited and inadequately protected. In many parts of the world, groundwater use is poorly controlled; in others, groundwater is heavily polluted. It may well be that much of this pollution has yet to be detected, given the slow flow rates of groundwater and the volume of storage involved. What we know of pollution levels in aquifers may be only the tip of an underground iceberg. There is, in any case, no doubt that this important resource urgently needs to be better protected.

Protecting groundwater resources

There are two basic means of protecting groundwater resources:

- *controlling groundwater abstraction,* particularly in areas subject to irreversible side-effects such as saltwater intrusion and land subsidence; and
- *controlling groundwater pollution* with a combination of techniques that include evaluating aquifer pollution vulnerability, assessing potential contaminant loads and implementing land-use plans specifically designed to protect groundwater resources.

Jeff Davies/British Geological Survey

Unprotected spring sources are still widely used for drinking water supplies and are highly vulnerable to surface contamination. They are responsible for the spread of many water-borne diseases, particularly among children.

Controlling abstraction

The control of groundwater abstraction is the first priority since, in many urban areas, large numbers of boreholes have been drilled in shallow aquifers without regard to the overall yield, the rights of other users or their effect on salt water intrusion and land subsidence.

Controlling abstraction requires a number of legal and administrative steps. National governments need first to declare groundwater a 'natural resource available for public use in a controlled fashion'. This establishes the legal precedent for control. A government agency can then be appointed to develop and implement a series of detailed regulations and codes covering groundwater abstraction. This agency will issue permits for the development of groundwater resources such as well digging, spring capture and borehole drilling. The permit normally specifies the depth, diameter and allowed intake of the installation.

The next stage is to issue licences to abstract groundwater, where this is appropriate. This is not always the case

Source protection zones

Boreholes and springs may need individual protection in addition to the protection provided for the aquifer. This can be provided by a 'source protection zone' around the borehole within which potentially polluting activities are restricted.

In Western Europe, these source protection zones can be complex and relatively large, and may encompass all the recharge capture area for the source. To eliminate all risks of contamination, all potentially polluting activities would have to be prohibited or controlled within the protection zone. In practice, the capture zone is divided into two or three sub-zones and the most severe restrictions are applied only close to the source.

An inner protection zone has been widely recommended to protect against the effects of human activity. The principal concern is the prevention of pathogenic contamination and is based on accepted biological (principally bacteriological) decay criteria. The extent of the zone is often defined by the horizontal saturated zone groundwater flow travel time, and travel times of 50 to 100 days have been adopted by several European countries. The inner zone includes the operational area immediately around the wellhead, where activities are restricted to those related to water abstraction itself. The dimension and shape of this area are necessarily somewhat arbitrary as they depend in part on the geological and soil formations present. A radius of 30–50 metres appears reasonable from experience in the United Kingdom.

Few cases of pathogenic contamination have occurred where the horizontal distance between the borehole or spring and the proven source of pollution was equivalent to more than the distance travelled by groundwater in 20 days, despite the fact that pathogens are capable of surviving in the sub-surface for up to 400 days.

In some African countries, similar but less complicated protection zone guidelines have been adopted. Rural water supplies in particular are rarely treated, so protection of these sources is especially important. Rural community water supply wells or boreholes often have a sloping concrete apron around the source to prevent spilled water leaking back into the wellhead. Animals are prohibited from the area immediately around the source and instead water is discharged into animal-watering troughs some distance from the well.

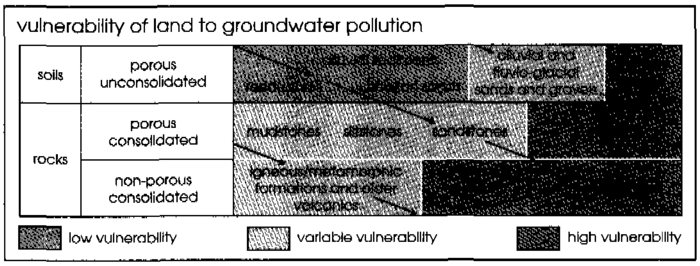
A circular protection zone 50–100 metres in radius can be introduced to reduce the risk of pathogenic contamination. Within this zone pit latrines, septic tanks and other potential sources of sub-surface contamination are not allowed. The extent of this zone may need to be increased where recharge and flow to the well is along fissures, because travel times are so much faster. Karstic limestones and poorly weathered basement are especially vulnerable in this respect.

and it is often neither profitable nor practical to insist on licences for small users, especially those using spring water. Regulatory agencies can charge for construction permits and for abstraction licences. Charges can be based both on the volume of water abstracted and the use that is made of it. While abstraction licences are a useful means of generating income to finance the regulatory function, issuing construction permits in the first place is a better means of controlling groundwater development.

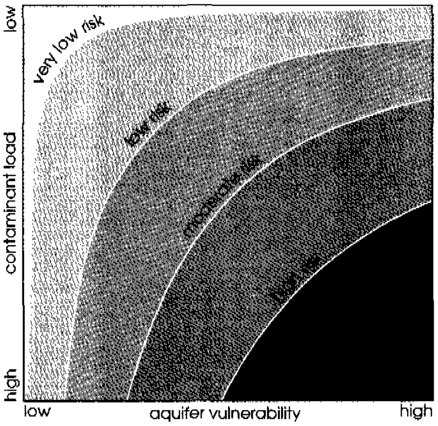
Regulations of this kind can be unpopular, particularly in relation to a resource that has historically been regarded as a common good freely available to anyone who wants it. Regulatory agencies therefore need sound public relations campaigns to inform the public of what they are doing, and why. They should also provide free advice to drilling contractors.

Aquifer vulnerability and pollution load

The risk of groundwater pollution is determined by the vulnerability of the aquifer to pollution and the loading of potential pollutants to which it may be subjected. Vulnerability depends partly on the extent to which pollutants are attenuated between the land surface and the water table, and partly on the rate with which water and its accompanying pollutants travel through the aquifer. Since pollutants travel much faster in the aquifer than in the soil and unsaturated layer above it, the nature of the material within the aquifer is of great importance in assessing vulnerability. The most vulnerable aquifers are composed of highly fractured rock such as limestone and have shallow water tables. Pollutants reach the water in such aquifers in a just a few days with little or no attenuation. The least vulnerable aquifers are those where pollutants take many years or decades to travel down to the saturated zone, as is the case with many semi-confined aquifers.



The risk of groundwater contamination depends on two factors: the contaminant load and the vulnerability of the aquifer to pollution.



Controlling groundwater pollution

The first requirement in the control of groundwater pollution is to assess the vulnerability to pollution of the nation's aquifers. The basic principles of vulnerability are well understood (see box on left) and a map of aquifer vulnerability will indicate the zones most in need of protection. The risk of contamination, of course, depends on the nature of the threat. Some industries are much more likely than others to lead to groundwater contamination (see list on page 27).

It is important to distinguish between point sources of pollution, such as landfills and specific industrial discharges, and the diffuse sources of pollution produced by the application of fertilizer and pesticides in agriculture and, to a lesser extent, from atmospheric deposition.

Efforts should be made to reduce pollution from point sources by improving waste disposal practices, paying particular attention to practices in areas where aquifers are highly vulnerable. In sensitive areas, land-use planning regulations should be introduced to restrict the kinds of industrial activity to be practised or developed.

Where there is widespread diffuse pollution from agriculture, restrictions may have to be made on the quantities of fertilizers and pesticides that can be applied, or on the crops that can be grown. Where salinity and waterlogging are being caused by irrigation, it may be possible to persuade farmers to switch to dryland crops, such as figs and grapes.

Finally, when plans have been made and put into place for the control of both abstraction and pollution, a monitoring and assessment programme will be needed to provide feedback on the success of these plans and to provide early warning of possible future threats.

Assessing groundwater resources

The need to protect groundwater resources is pointing up the need for more reliable data on both the quality and the quantity of water in aquifers, and on how they are changing. Such data can only be provided by well constructed monitoring systems. Groundwater monitoring is largely a national responsibility but, because groundwater does not respect national boundaries, assessment of the results needs to be carried out at national, regional and international levels.

National monitoring

Improved monitoring systems need to be set up in many countries to provide information on the rates of depletion of aquifers and the deterioration of groundwater quality. Monitoring can also provide managers with feedback on the effects of their policies. It is important that water quality monitoring includes assessment of levels of synthetic organic compounds that are widely used in industry and agriculture. In areas where large populations are still not connected to mains sewerage systems, it is also important to monitor microbiological pollution indicators.

However, monitoring groundwater quality and quantity provides no early warning of pollution. By the time pollutants show up in groundwater, the major damage may already have been done. Monitoring networks should therefore be developed to include monitoring of pollution loads, particularly in vulnerable recharge areas. The key elements of such an early warning monitoring strategy are shown in the table below.

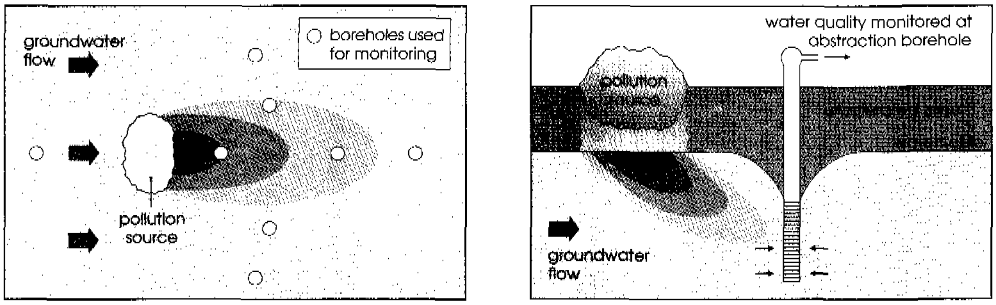
Groundwater quality monitoring has at least four objectives, which need to be carefully distinguished in the design of monitoring systems:

Key elements in an early warning monitoring strategy.

( ) brackets indicate less common or uncertain
FC = faecal coliforms

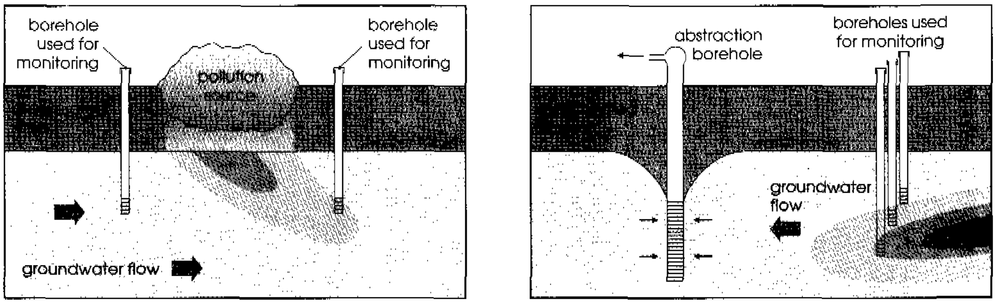
		[illegible]			semi-confined
		fractured	**granular**		
			thin unsaturated zone	**deep unsaturated zone**	
travel time from surface to saturated aquifer zone		hours-weeks	days-months	years-decades	decades +
pollution risk	**chemical**	high	high for mobile compounds	high for mobile and persistent compounds	moderate for persistent compounds only
	bacteriological	high	moderate	low	very low
early warning monitoring required		monitor at water table	monitor at water table	1. monitor unsaturated zone 2. monitor at water table	monitor semi-confining layer and aquifer
pollution indicators	**domestic wastewater**	Cl, NO_3, (NH_4), SO_4, FC	Cl, NO_3, (NH_4), SO_4, FC	Cl, NO_3, (NH_4), SO_4, (FC)	Cl, NO_3, (NH_4), SO_4
	industrial effluent	chlorinated hydrocarbons, wide range of other organic compounds, metals	metals, range of organic compounds	persistent organics, (metals)	persistent organics, (metals)

Four types of groundwater quality monitoring: evaluation monitoring, drinking water surveillance monitoring, and offensive and defensive detection monitoring.



evaluation monitoring (plan view)

drinking water supply surveillance



offensive detection monitoring

defensive detection monitoring

Dependence on groundwater for drinking water in the European Community (1976)

Denmark, 98%
Italy, 93%
German Federal Republic, 71%
Belgium, 71%
Luxembourg, 70%
Netherlands, 64%
France, 50%
United Kingdom, 31%
Ireland, 15%

- definition of the extent of groundwater pollution (evaluation monitoring);
- quality control of groundwater used as drinking water (drinking water supply surveillance);
- early discovery of groundwater pollution from a given activity (offensive detection monitoring); and
- provision of advance warning of the arrival of polluted water at important sources of supply (defensive detection monitoring).

Information from national monitoring programmes of this type does not, of course, provide an overall picture of the condition of individual aquifers, some of which extend across at least one national boundary. There is therefore a need to synthesize national assessments on a regional or international basis.

Regional and international action

A number of important regional assessments of groundwater resources have already been made.

In 1982, the Directorate-General for the Environment, Consumer Protection and Nuclear Safety of the European Community produced a major assessment of groundwater resources within its (then) nine member states. It consisted of a general survey (*Groundwater Resources of the European Community: synthetical report*) and individual reports for each member state. These reports dealt with four major themes:

- the aquifer inventory—location and type;
- groundwater hydrology—flows within these aquifers;
- groundwater abstraction; and
- groundwater availability by area.

The study concluded that the Community had enough groundwater to meet most of its needs but that in most countries abstraction rates were already high—Belgium was abstracting some 70 percent of its available groundwater resources, Denmark 40 percent, France 25–50 percent, Italy 50 percent, Luxembourg 37 percent, the Netherlands 62 percent and the United Kingdom at least 25 percent. Only Ireland, which was abstracting only 3 percent of its groundwater resources, had major untapped resources.

This assessment was concerned mainly with groundwater quantity. Since it was published, attention has turned in Europe (and the United States) to quality, and not only have groundwater quality monitoring programmes been greatly expanded but many groundwater protection schemes have been put into place.

Two other regional assessments (on which this publication is largely based) have been prepared for the Latin American-Caribbean and the Asia-Pacific Regions. The first of these is part of a regional groundwater pollution control programme being developed by the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) which has its headquarters in Lima, Peru. It consists of seven reports covering the general situation, the extent of groundwater pollution, risk assessment, monitoring, protection and the impact of wastewater reuse. The studies were carried out by members of the staff of CEPIS and the British Geological Survey with financial support from the World Health Organization, the Pan American Health Organization and the UK Overseas Development Administration.

The most recent GEMS/Water assessment is for the Asia-Pacific Region, which has been carried out by the British Geological Survey. The report assesses the impact of urbanization, industry and agriculture on groundwater quality, and makes a number of recommendations on groundwater protection and monitoring.

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