GROUND-WATER POLLUTION

International Hydrological Programme

Contents

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Ground-water pollution

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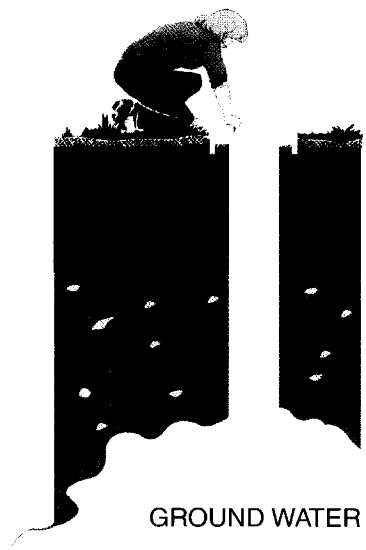
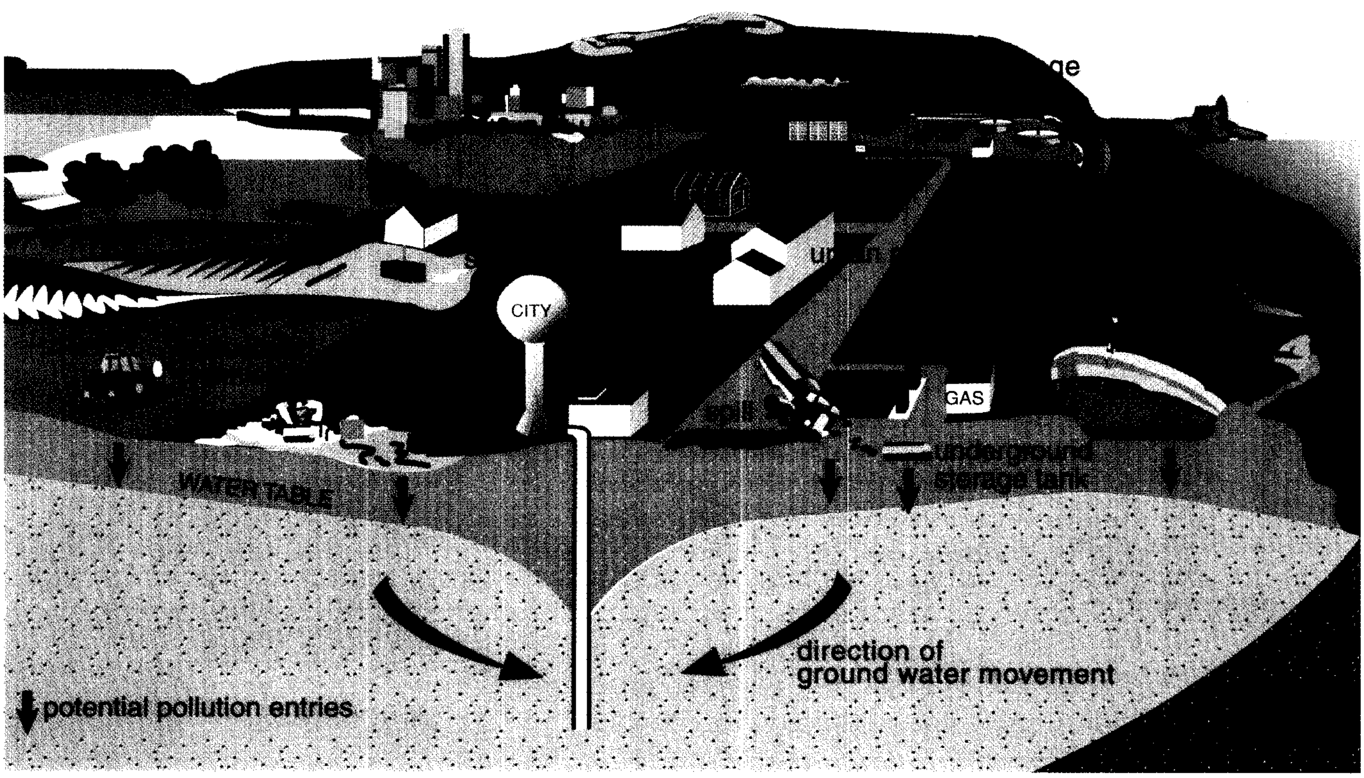
Introduction

Most people have never heard of ground water. That is no surprise, because it is not readily visible—ground water is one of the world's "hidden" resources. However, many of those who have heard of ground water consider it a pristine source of drinking water that cannot be polluted because it is naturally protected from pollution by layers of soils and rocks.

Yet, pollution of ground water has always been with us because of its close link to human activities. Practically every human activity, every type of facility or structure installed by man represents a potential source of pollution. For centuries man has been disposing of waste products by placing them in streams, storing them on the ground, or, by various methods, putting them into the ground. Every day, a wide variety of potentially harmful substances is regularly introduced into the subsurface rock formations and the aquifers. Thus, ground-water pollution, as any other form of pollution, is the price the civilised world must pay for its existence.



The causes of ground-water pollution are numerous and are as diverse as the activities of man.



Ground water in its natural environment

Importance of ground water

Ground water
is underground water which is visible when it emerges from springs or is removed by wells. Ground water is part of the hydrological cycle and is closely related to surface water.

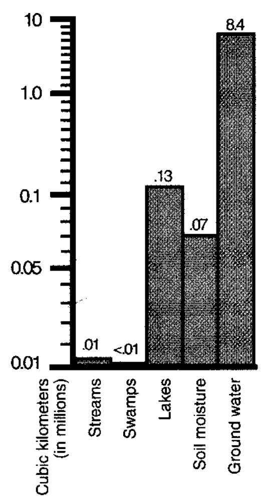
Water is vital to man's existence. Early human civilisations centered around springs and streams. Many civilisations that flourished after developing reliable water supply collapsed when the supply was exhausted or its quality deteriorated. Throughout history, people around the world have used ground water as a source of drinking water, and even today, more than half the world's population depends on ground water for survival (UNESCO, 1992).

There are good economic reasons for this dependence: ground water in its natural state is usually of excellent quality and does not require much treatment. In most cases, ground water can also be inexpensively tapped immediately adjacent to or close to the point of use, thereby saving pumping and distribution costs. Other reasons why ground water is a preferred source of water supplies are that it is a widely distributed, stable, and dependable source and groundwater reservoirs represent built-in storage facilities.

Ground water has a number of vital economic and social functions, which are not always fully recognised and appreciated. First, ground water is a very important source for public, private, agricultural, and industrial water supply and a main source of continual streamflow in some regions. Many streams would dry up in long dry seasons or in winter were they not fed by ground water. Besides that, ground water is of vital importance for the diversity, sustainability, and survival of ecosystems.

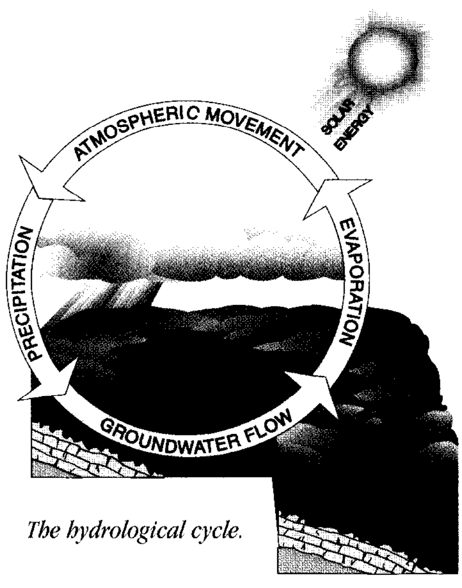
Origin of ground water

Distribution of the world's unfrozen freshwater supply



Ground water is an important part of the earth's water cycle—a dynamic, never-ending movement of water from ocean to atmosphere, to land, and back to the ocean, driven by solar energy. All water in this hydrological cycle is derived from the ocean by evaporation.

It has been estimated that the total world's water supply is 1,360 million km^3 (Nace, 1971), most of which (97%) is stored in the oceans. Estimates of global water supply show that ground water represents about 0.6 percent of the total water or 22 percent of all the world's fresh water. If we exclude from consideration water frozen in glaciers and ice caps, which hold most of fresh water (77%), ground water accounts for 98 percent of the total volume of fresh water.



The hydrological cycle.

Ground-water occurrence and movement

Understanding how ground water occurs and moves is the key to understanding ground water. Contrary to popular belief, ground water does not occur in underground veins or streams. It simply fills numerous openings in subsurface rocks—pretty much as water fills a sponge.

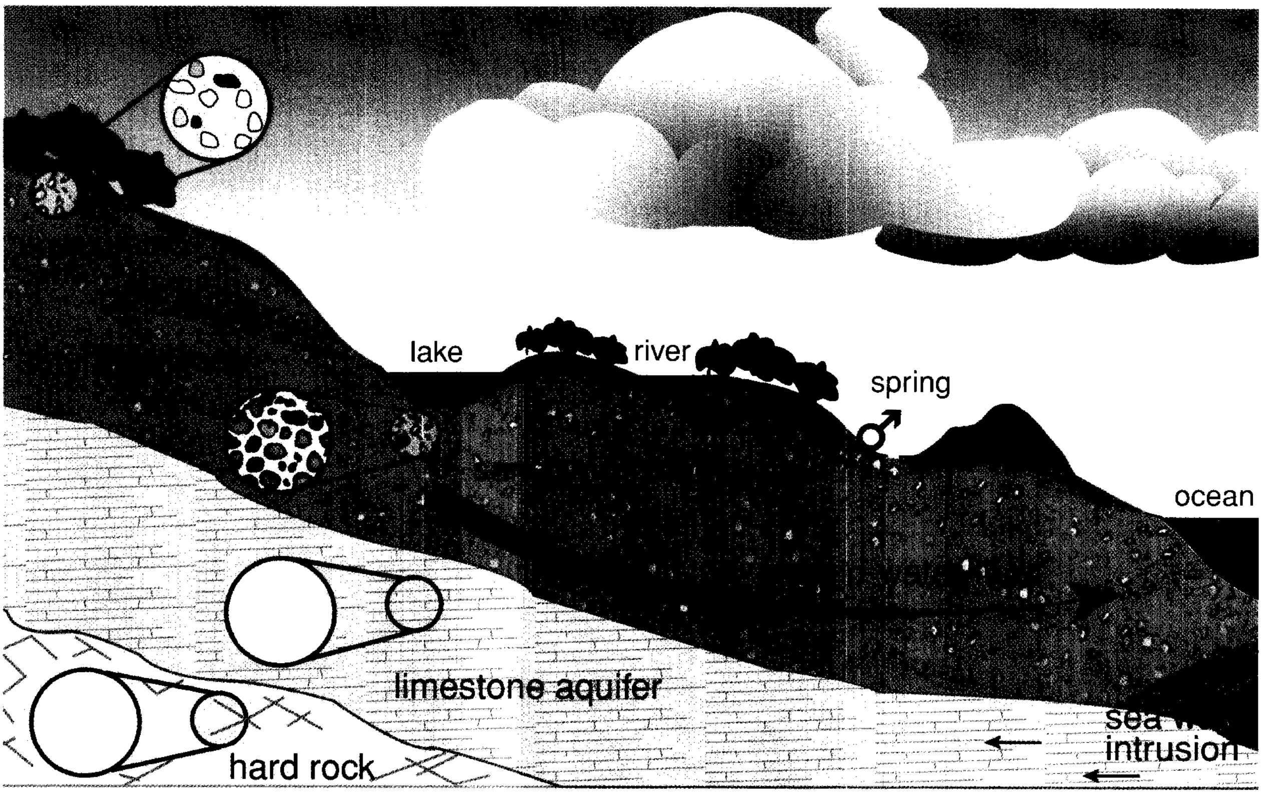
Practically all ground water originates as precipitation. Water falling on the surface soaks through the ground and moves downward through the ***unsaturated zone*** under the force of gravity. Once it reaches the top of the saturated zone, called the ***water table***, it replenishes the ground water, which is stored in water-bearing layers called ***aquifers***.

Aquifers consist either of unconsolidated material (such as sand or gravel) or consolidated rocks (such as sandstone). Unconsolidated materials can store large volumes of water in the pore spaces among the grains (up to 30% of their total volume). In consolidated, more or less solid, rocks water is stored primarily in fractures but also in pores, which are smaller than those of the unconsolidated materials. In some rocks, such as limestone, water is stored in fractures enlarged as the rock is dissolved away.

Ground water can move sideways as well as up or down. This movement is in response to gravity, differences in elevation, and differences in pressure. As a general rule, ground water moves toward lower-lying places and ultimately discharges in streams, lakes, and springs. Ground water moves through the aquifers very slowly, with flow velocities measured in fractions of meters per day or meters per year, compared to meters per second for streamflow.

Water infiltrating into the ground passes first through the unsaturated zone, which is filled with both air and water. The underlying saturated zone is fully filled with water, commonly called ground water.

Aquifers consist of water-bearing layers of granular deposits or permeable rocks that store and transmit water freely.



Natural quality of ground water

Most ground water needs no treatment and is a readily available source of drinking water.

The value of ground water lies not only in its widespread occurrence and availability but also in its consistent good quality, which makes it an ideal supply of drinking water. The term ***quality of water*** refers to its physical, chemical, and biological characteristics as they relate to the intended use of water.

Water in nature is never "pure water." Atmospheric precipitation (rain or snow), which is the principal source of ground water, always contains small quantities of dissolved mineral salts, suspended solids, gaseous products, and other "common impurities."

The original quality of ground water is given by the quality of precipitation water. It is further modified by reactions with organic matter, soils, and rocks over time. In general, ground-water quality tends to be relatively uniform within a given aquifer, both with respect to location and time. But that does not mean that in different locations major contrasts in natural quality cannot be noted.

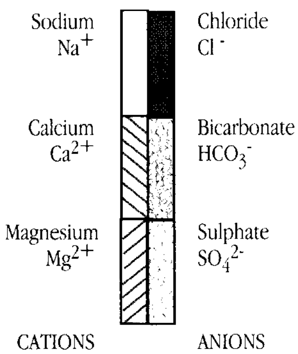
Ground water nearly always contains more mineral matter than nearby surface water, although both originate as precipitation. The main reason for this is that water is a slightly acidic solvent, and is capable of dissolving many substances. From the moment rain falls to the ground and begins infiltrate and pass through soils and rocks, the water dissolves the host materials and minerals are added to the ground water flowing through.

The chemical composition of ground water is determined by the composition and physical properties of the materials it contacts and by the length of the contact. Generally, the longer the period of contact, the more minerals are dissolved. The chemical composition of ground water can also indicate its origin and history because ground water takes on the character and properties of the materials through which it has passed (as already noted by Roman scholar Pliny in the first century).

The number of major dissolved constituents in ground water is quite limited and the natural variations are not as great as might be expected from the complex mineral and organic material through which the water has passed and from the complexity of processes involved. Only nine constituents constitute the bulk of the chemical composition; most common of them are: sodium, calcium, and magnesium, which combine chemically with chloride, bicarbonate, and sulphate to form the majority of mineral salts in ground water.

All particles forming the minerals are electrically charged and are called ***ions***. Positively charged ions are called ***cations***; negatively charged, ***anions***. In general, the sums of cations and anions in ground water should be equal. Concentrations of dissolved constituents generally are small, and are measured in milligrams per litre (mg/l).

Six major ions normally form 95 percent of the chemical composition of ground water:



Chemical constituents in ground water

Major Constituents	Selected Trace Constituents
Calcium	Aluminium
Magnesium	Arsenic
Sodium	Cadmium
Potassium	Chromium
Bicarbonate	Cobalt
Carbonate	Copper
Chloride	Lead
Sulphate	Mercury
Silica	Nickel
Minor Constituents	Phosphate
Iron	Radium
Manganese	Selenium
Strontium	Silver
Fluoride	Uranium
Nitrate	Zinc

Ground water also is cleaner than most surface water because the earth materials act as natural filters to screen out some bacteria and impurities from the water passing through. Most ground water contains no suspended particles and practically no bacteria or organic matter. It is usually clear and odourless. Most of the dissolved minerals are rarely harmful to health, are in low concentrations, and may give the water a pleasant taste.

Some of the dissolved minerals are even essential for good health, but others, if too abundant, may be toxic or cause taste or odour problems. Recognition of the fact that some of these dissolved substances may be objectionable or even detrimental to health resulted in the development of drinking water standards.These standards serve as a basis for appraisal of the results of chemical analyses and are based on the presence of objectionable properties or substances (taste, odour, colour, dissolved solids, iron, etc.) and on the presence of substances with adverse physiological effects.

The chemical constituents in ground water determine its usefulness for households, industry, and agriculture. Water of different quality is needed for different purposes.

Water for general household use includes water for drinking, cooking, dishes, laundry, and bathing. This water should taste and smell good, be free of harmful bacteria and substances, and should not stain washed cloths and dishes or clog appliances and plumbing. Industrial water should be, in general, non-corrosive, not too hard, non-scaling, and non-staining. Water required for irrigation should be low in sodium and should not have too many minerals—especially boron, which is toxic to plants. One of the properties of ground water, which makes it an ideal source for all uses, is its uniform, regionally nearly constant temperature.

"Water is the source of health."
Proverb of Sierra Leone

Recommended limits for inorganic constituents in drinking water, in milligrams per litre (mg/l)

OBJECTIONABLE SUBSTANCES		POTENTIALLY HARMFUL SUBSTANCES	
Aluminium (Al)	0.2	Arsenic (As)	0.01
Ammonia (NH4)	1.5	Barium (Ba)	0.7
Chloride (Cl)	250	Boron (B)	0.3
Sulphide (H2S)	0.05	Cadmium (Cd)	0.003
Iron (Fe)	0.3	Chromium (Cr)	0.05
Manganese (Mn)	0.05	Copper (Cu)	2
Sodium (Na)	200	Fluoride (F)	1.5
Sulphate (SO4)	250	Lead (Pb)	0.01
Zinc (Zn)	3.0	Mercury (Hg)	0.001
Total dissolved solids	500	Molybdenum (Mo)	0.07
		Nickel (Ni)	0.02
		Nitrate (NO_3)	50
		Selenium (Se)	0.01

Source: WHO Guidelines, 1993.

Principal properties important to use of ground water

HOUSEHOLD	INDUSTRY	IRRIGATION
TASTE		
ODOR		
POISONS	pH	
FLUORIDE	ACIDITY	
NITRATE	ALKALINITY	
IRON	SILICA	BORON
HARDNESS	HARDNESS	ALKALINITY
SEDIMENT	SEDIMENT	SODIUM-CALCIUM RATIO
DISSOLVED SOLIDS	DISSOLVED SOLIDS	DISSOLVED SOLIDS

Source: U.S. Geological Survey, A primer on ground water, 1963.

Ground-water pollution

Extent of pollution

Ground-water pollution
is a modification of the physical, chemical, and biological properties of ground water, restricting or preventing its use for which it had previously been suited.

Until about 25 years ago, relatively little attention had been focused on ground-water pollution, probably because the problem was out of sight, and thus out of mind. Although pollution of ground water is not a new phenomenon, it had not appeared as a new environmental challenge until the late 1970s. Before then, it was a relatively obscure problem because ground water was believed to be naturally protected from pollution by the layers of soils and rocks between the earth's surface and the water table. Since then, however, every nation has reported cases of ground-water pollution, with some instances receiving widespread publicity.

The first major–or the most publicised–incident was Love Canal in Niagara Falls, a small city in the State of New York, USA, where in 1978 people were evacuated from their homes after hazardous waste buried for more than 25 years seeped to the surface and into basements and polluted ground water. The area was declared a national disaster. Love Canal is probably one of the most infamous pollution sites in the world and is an important environmental benchmark because the events of 1978 fixed in the public's mind a belief that ground water anywhere could not really be trusted because of the risk of unknown chemical pollution. And this negative image for ground water has been reinforced over the years by media sensationalism about pollution.

Although the pollution of ground water is prevalent and omnipresent, it is largely localised and only a small part of the earth's ground-water resources may now be impaired. For example, it has been estimated that about one to two percent of the area of usable aquifers in the United States may be presently polluted. The problem, however, may be that these affected parts may well be in urban areas where the ground-water pollution threat is the greatest and the water is needed the most.

Ground-water pollution in Europe

Man has lived in urbanised areas of Europe for centuries, and in some cases, for more then two millennia. Population concentrations have created a slowly increasing pollution of the soil and ground water beneath the cities. Presently, it has been estimated that 20,000 - 60,000 km^2 of the area of the ground-water system in the European Communities, which amounts to 2-4 percent of the soil surface, may be polluted within a period of 50 years, if no action is taken. In addition, modern agriculture has turned into a significant source of ground-water pollution. The European Community is the largest user of agrochemicals in the world. Nitrate leaching at a level of 50 mg/l and more occurs in about 25 percent of the agricultural soils. Computations indicated that in 65 percent of all agricultural land the EC standard for the sum of pesticides (0.5 µg/l) will be exceeded.

An estimation of the magnitude of the polluted urban and industrialised area in the European Communities

Source	Number	Area *	Potentially polluted area *
Industrial facilities	12 million	10,000	16,000 - 40,000
Landfills & Impoundments	60,000 - 120,000	600 - 1,200	900 - 7,200
Fuel storage tanks	3-6 million	–	250 - 4,000
Mining waste Dump sites	few thousand	250 - 500	350 - 5,000
Line sources	–	10,000 - 25,000	1,500 - 7,500
Dredged sediment dump sites	hundreds	–	hundreds
Hazardous waste sites	hundreds	–	hundreds
Estimated total polluted area			**20,000 - 60,000**

***area in km^2**

Source: Sustainable use of groundwater—problems and threats in the European Communities, 1991.

Naturally-occurring pollutants

Substances that can pollute ground water can be divided into substances that occur naturally and substances produced or introduced by human activities. Naturally-occurring substances causing pollution of ground water include iron, manganese, toxic elements, and radionuclides. Substances resulting from human activities include, for example, bacteria, viruses, nitrates, synthetic organic chemicals and hydrocarbons (e.g. solvents, pesticides, petroleum products), and heavy metals.

Very often, in our quest to fight ground-water pollution, we tend to forget that there are a few natural sources of pollution that cannot be eliminated or removed—the naturally-occurring chemical constituents, leached from soils or rocks by percolating water in concentrations that impair the use of ground water. Some of them are quite innocuous, causing only inconveniences, such as iron and manganese. But others may be harmful to human health, e.g. toxic elements (such as arsenic or selenium), fluoride, or radionuclides (radium, radon, and uranium).

Some of the most common water quality problems encountered in drinking water are caused by naturally-occurring minerals. Among those are calcium and magnesium compounds, high concentrations of which cause hardness of water, and iron and manganese.

Hard water is not harmful, and in fact it has a pleasant taste and may be beneficial to health. The most commonly noticed effect of hardness is its tendency to prevent soap from lathering and to form soap scum. It also results in scale formation and incrustations in containers or conduits where water is heated or transported. Calcium and magnesium rich waters are especially abundant in limestone terranes.

Most water supplies contain some iron because iron is widely distributed in the earth's crust. Concentrations in ground water higher than 0.3 mg/l are a common nuisance. Iron does not cause health problems but is of considerable concern for aesthetic and taste reasons. On exposure to air, iron oxidises to a reddish-brown precipitate, which can cause discolouration of water and stains on washed cloths, dishes, utensils, and plumbing fixtures and can clog pipes. Manganese causes similar problems as iron but the stains are black and much harder to remove than those from iron.

Iron-bearing water also favours the growth of iron bacteria, which create a gel-like slime that can coat submerged surfaces and clog pipes and openings around wells.

Hydrogen sulphide is a gas that is recognisable by its "rotten-egg" smell. It is caused by sulphate-reducing bacteria. Water containing hydrogen sulphide is corrosive and attacks plumbing systems.

Hard water and health

There is no evidence of permanent adverse effects from the consumption of hard water. But there have been quite a few studies indicating an inverse relationship between the amount of hardness and the incidence of heart disease. The first report came in 1957 from Japan, suggesting that areas with soft water tend to have high mortality rate from heart disease compared to areas with hard water. Since then studies conducted in the United Kingdom, United States, Sweden, and the Netherlands reached the same conclusion.

Common water quality problems

INDICATION OF PROBLEM	PROBABLE CAUSE
Mineral scale build-up in kettles and plumbing.	Hardness of water (high calcium and magnesium).
Rusty or black stain on laundry and utensils.	Iron and/or manganese.
Red to brown slime in plumbing and toilet tanks.	Iron bacteria.
"Rotten-egg" smell/taste. Corrosion of plumbing.	Hydrogen sulphide and/or sulphate reducing bacteria.
Salty taste.	Chloride—saline water.

Source: Geological Survey of Ireland Circular 85/1.

"Poison is in everything, and no thing is without poison. The dosage makes it either a poison or a remedy."
Paracelsus (1495-1541)

Some elements have harmful effects if present in drinking water above certain limits.

Arsenic is widely distributed in the environment and is usually found in compounds with sulphate. Arsenic is highly toxic at concentrations above 0.01 mg/l, and high doses cause rapid death. Chronic poisoning by small doses results in skin lesions, hyperkeratosis, and skin cancer.

Selenium, a naturally-occurring, non-metallic element present in soils and rocks is believed to be essential to human and animal nutrition in minute amounts but can be toxic at relatively low concentrations (0.01 mg/l). Its prolonged intake causes central nervous system and gastrointestinal disturbances, skin discolouration, and bad teeth. Selenium toxicity has been observed in many parts of the world. The primary source of selenium is volcanic activity.

Fluoride is considered beneficial for prevention of dental caries and is added to some water supplies for promotion of dental health. But in high concentrations (above 2 mg/l) it causes dental fluorosis ("mottled enamel") or skeletal fluorosis. Most fluoride is derived from fluorine-rich rocks, and the highest concentrations are associated with granite and volcanic rock.

Natural radioactivity and its effects on human health recently have become a major environmental concern because of the discovery of widespread occurrence of elevated levels of radon in areas underlain by granite or phosphorites containing uranium minerals. Radon and other radionuclides such as radium or uranium are found as trace elements in most rocks and soils and are formed principally by radioactive decay of uranium and thorium isotopes. The occurrence and distribution of radium and uranium in ground water is controlled primarily by the local geology and geochemistry. Consumption of water containing radium and, to a lesser degree, uranium can cause a significant accumulation of those radionuclides in human bone tissue, and ultimately lead to cancer.

Arsenic poisoning in Bangladesh

In an effort to bring safe drinking water to Bangladesh, international aid agencies unwittingly tapped into ground water containing naturally-occurring arsenic, and tragically caused the largest mass poisoning in the world. Now, thousands are dying a slow death. Dangerous levels of arsenic have been found in this ground water. Based on the initial survey results, arsenic levels exceeding the WHO limit of 0.01 milligrams per litre have been found in parts of 43 of Bangladesh's 64 districts. It has been estimated that possibly 35 million people are drinking water polluted by arsenic, and therefore, are at risk.

Arsenic is present in many rock-forming minerals. Its concentrations are particularly high in ground water drawn from pyrite-rich sedimentary aquifers, such as the alluvial aquifers in the Bengal delta region of Bangladesh and India.

This incidence of ground-water pollution by naturally-occurring arsenic is by no means a local or isolated one. It has also been reported from Argentina, Chile, Ghana, India, Mexico, Mongolia, and Taiwan.

Pollutants introduced by human activities

Polluting substances resulting from human activities primarily include organic chemicals, pesticides, heavy metals, nitrate, bacteria, and viruses. They are introduced into ground water from a variety of sources. Man's recognition of the damage brought about by his activities has been slow, almost as slow as some environmental after-effects.

The type of ground-water pollution of the greatest concern today—at least in the industrialised countries—is pollution from hazardous chemicals, specifically organic chemicals.

More than 600 organic compounds have been detected in drinking water supplies. The use of these hazardous chemicals is ubiquitous; substances found in polluted ground water are used in everything from lumber treatment to electronics manufacturing, fuels, food production, and agricultural chemical synthesis. When used, stored, or disposed of on land, these chemicals may eventually migrate to the ground water below.

In general, concentrations of organic compounds in ground water are too low to produce acute toxicity, but the effects of long-term, continual ingestion might well represent a serious public health problem.

The most common of these substances are volatile organic compounds, which are used in many everyday products such as paints, dyes, household cleaners, and aerosol sprays and in industry as solvents and lubricants.

Pesticides used in agriculture and forestry are mainly synthetic organic compounds. The term pesticide includes any material (insecticide, herbicide, and fungicide), used to control, destroy, or mitigate insects and weeds. Many of the pesticide constituents are highly toxic, even in minute amounts.

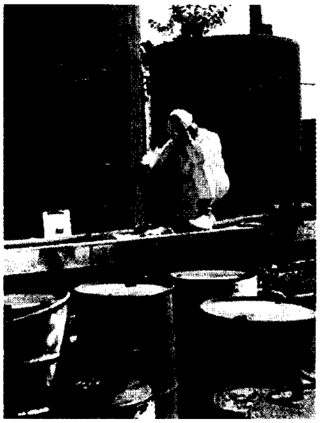
Heavy metals are used in various ways as raw materials for numerous industrial products or as catalysts in chemical processes. The most frequently reported cases of pollution involve lead, arsenic, chromium, cadmium, zinc, copper, barium, and nickel.

Nitrate is the most commonly identifiable pollutant in ground water in rural areas. Nitrogen in the form of dissolved nitrate is the major nutrient for vegetation, and an element essential to all life. But there is ample evidence of widespread nitrate pollution of ground water caused by the inefficient application of nitrogen-based fertilisers. When applied, some nitrate is retained by plants and soil particles. However, if applied in excessive amounts, the excess nitrate not consumed by plants can be flushed down to ground water. Although nitrate is relatively non-toxic, it can cause, under certain conditions, a serious blood disorder in infants.

The greatest danger associated with drinking water is that it may be polluted by human or animal waste, and lead to ingestion of dangerous pathoge ns. The organisms most commonly used as indicators of pollution are coliform bacteria, common bacteria found in human waste. They are relatively harmless themselves, but their presence in drinking water may indicate the presence of other, more harmful bacteria, viruses, or other pathogens.

"Blue babies"

High concentrations of nitrate can result in a serious, though easily treated, blood disorder in infants under 6 months of age--and in extreme cases in death--called methemoglobinemia, or popularly "blue baby syndrome." The problem is that under favourable conditions, nitrate can be reduced to nitrite by denitrifying bacteria in the upper digestive tract of some infants. The reaction of nitrite with hemoglobin of the blood reduces the capability of the blood to carry oxygen, and the skin of affected infants takes on a bluish tone. Prompt medical care normally results in quick recovery.

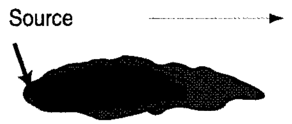


Abandoned chemicals in leaky barrels are a great danger to ground water.

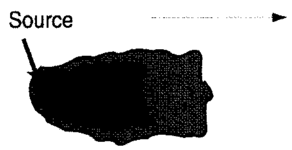
Origin and transport of pollutants

Types of pollution plumes (plan view)

Direction of ground-water flow



Continuous release of a pollutant and rapid flow creates a long, narrow plume.



Continuous release of a pollutant and slow flow creates a wider plume.

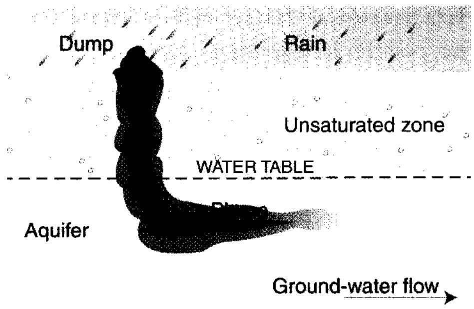
Intermittent release of a pollutant creates a series of small plumes with decreasing concentration.

Pollution of ground water is the result of interactions between the pollutant(s), available moisture, subsurface materials, and ground-water flow system. Ground-water pollution can originate on the surface of the ground, in the ground above the water table, or in the ground below the water table. There are at least three ways by which ground-water pollution can occur: infiltration, direct migration, and interaquifer exchange.

Pollution by infiltration is probably the most common ground-water pollution mechanism. A pollutant released at the surface infiltrates the soil through pore spaces in the soil matrix and moves downward through the unsaturated zone under the force of gravity until the top of the saturated zone (the water table) is reached. After the pollutant enters the saturated zone (an aquifer), it travels in the direction of ground-water flow.

Pollutants can bypass the unsaturated zone and migrate directly into ground water if they are released from below-ground sources that lie just above or within the saturated zone. Old or improperly abandoned wells with deteriorated casing can allow direct migration of polluted water from the surface to the aquifer. Such wells also allow polluted water to migrate from one aquifer to another.

Where a pollutant originates is a factor that can affect its actual impact on ground-water quality. If a pollutant is released at or near the surface of the ground, it may have to travel through numerous layers of soil and other materials in the unsaturated zone before it reaches the ground water. As the pollutant moves through these layers, a number of the physical, chemical, and biological processes are in operation that lessen the eventual impact of the polluting substance once it finally reaches the ground water. The effectiveness of these attenuation processes increases with the increasing distance the substance has to travel and with the increasing amount of time it takes the substance to reach the ground water. The longer the distance and time, the greater the attenuation potential.



In the subsurface, pollutants travel first downward (through the unsaturated zone); and after reaching the water table, in the same direction as ground-water flow.

If it were possible to see zones of pollutants traveling in a ground-water system from an aerial view, most would appear very small in relation to the total area of the ground-water system. Pollutants from point sources (e.g. a dump) travel in a relatively compact, well-defined body, called a *plume*, along ground-water flow lines. Pollutants are less concentrated at the plume margins and the concentration increases toward the source zone. The shape and size of a plume depends upon the local geology, ground-water flow, type and concentration of a pollutant, and the continuity of the supply of a pollutant.

Although considerable progress has been made in recent years in ability to predict the distribution and transport of pollutants in the subsurface, each pollution site is unique and requires a thorough, site-specific evaluation. This is especially important in urban areas with the extensive networks of underground structures (sewers, tunnels, etc.).

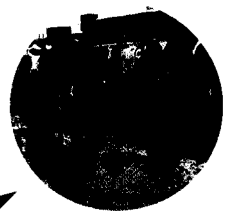
Sources of ground-water pollution

Sources of ground-water pollution are many and as diverse as urban, industrial, and agricultural land uses. Pollution sources can be either single sources at one specific location, called *point sources*, or innumerable sources dispersed over more extensive areas, which are referred to as *non-point sources*. Generally, point sources, e.g. landfills, wastewater lagoons, or underground tanks, are less prevalent in developing countries, due to lower industrial development and fewer municipal services. Ground-water pollution risks in developing countries are more often associated with non-point sources, such as agricultural activities, unsewered sanitation, and polluted urban runoff.

Pollution sources can be grouped into five general categories: municipal, industrial, agricultural, domestic, and environmental.

In urban areas, the major potential source of pollution is the ever-increasing volume of waste.

Animal waste is a potentially significant source of nitrate pollution in agricultural areas.



MUNICIPAL
- Solid waste disposal
- Wastewater impoundments
- Disposal of sewage sludge
- Leaking sewers
- Leaking underground tanks
- Improperly abandoned wells

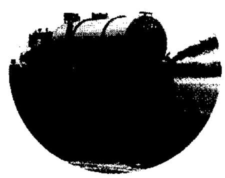
INDUSTRIAL
- Liquid waste disposal
- Hazardous waste storage and disposal
- Storage tank and pipeline leaks
- Spills of chemicals
- Mining waste (tailings, slurry lagoons)
- Injection wells
- Stockpiles, refuse piles
- Oilfield brines
- Salvage yards

AGRICULTURAL
- Animal feedlots
- Animal waste storage (manure pits)
- Fertiliser storage and use
- Pesticide storage and use
- Irrigation return flow
- Silage

DOMESTIC
- Septic tanks, cesspools, latrines
- Improperly constructed and abandoned wells
- Lawn fertilisers

ENVIRONMENTAL
- Saline water intrusion
- Dissolved and particular matter in precipitation
- Naturally-occurring pollutants

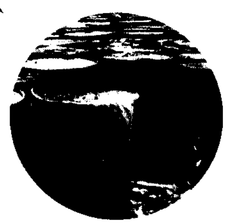
Overapplication of fertilisers and pesticides can lead to widespread ground-water pollution.



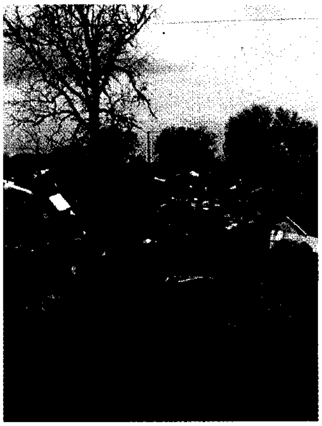
Proper installation of on-site sanitation systems reduces the risk of pollution.

In mining areas, leachate from spoil heaps can seriously pollute ground water.

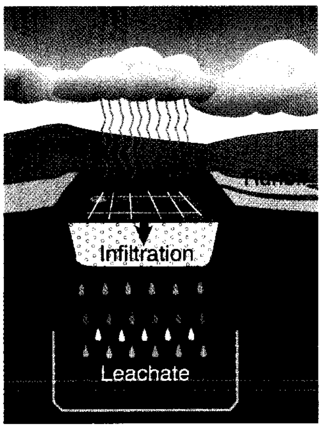
Old barrels at hidden dumps may contain chemicals and cause ground-water pollution.



Waste disposal



Uncontrolled dumping of garbage is one of the principal sources of ground-water pollution.



Water infiltrating through a landfill creates a highly mineralised, obnoxious liquid, called leachate.

Waste disposal practices seem to be the dominant sources of ground-water pollution. The growth of population and of industrial and agricultural production during the last 50 years has for the first time in the history of civilisation begun produce quantities of waste greater than the environment can absorb. And the least objectionable course of dealing with this problem has become to put the waste out of sight into the ground.

Large volumes of domestic, commercial, and industrial waste keep on accumulating in and around the cities and villages. Burial in a landfill is the most common means of disposing of municipal waste. Landfills range from uncontrolled dumps, where refuse is piled up with little or no regard to the environment, to carefully designed and operated sanitary landfills, in which the dumped refuse is compacted and covered daily with a layer of soil.

For many cities in developing countries, there are no arrangements for the proper disposal of refuse, and consequently, uncontrolled dumping occurs. Although it is known that the solution is the proper disposal of solid waste, the sheer volume of the waste hinders such disposal. Complicating the problem is the fact that acquiring land for use as dump sites is expensive.

The metropolitan area of Manila, for example, produces 3,500 tons of trash daily, most of it disposed of at a large dump. In China, the volume of refuse from 370 cities alone is 60 million tons per year. And in industrialised countries the volumes are even more astonishing. The amount of municipal waste generated in the 12 countries of the European Communities is in the order of 100 million tons annually. And in the United States, the annual volume of municipal solid waste is more than 200 million tons.

Solid waste deposited in landfills decomposes and produces a leachate that can pollute underlying ground water. Because the amount of leachate produced in a landfill depends primarily on the amount of precipitation, in arid zones little or no leachate is produced. The chemical composition of leachate depends on the nature of refuse, on the leaching rate, and on the age of the fill. Concentrations of the various components decrease with time and eventually reach relatively stable levels.

To minimise adverse effects of landfills, flow of leachate to ground water must be reduced by lining the landfill bottom with impermeable natural material (clay) or plastic and collecting the leachate by drains, and by covering the landfill with fine soil as soon as it has reached the desired height. Landfills should be preferably located in fine-textured soil materials with a relatively deep water table to retard percolation of leachate to ground water.

Typical composition of leachates from recent and aged domestic refuse

Components (in mg/l, except pH values)	Leachate from recent waste	Leachate from aged waste
pH value	6.2	7.5
COD (chemical oxygen demand)	23,800.0	1,160.0
BOD (biological oxygen demand)	11,900.0	260.0
TOC (total organic carbon)	8,000.0	465.0
Ammonium-nitrogen (NH_4-N)	790.0	370.0
Oxidized nitrogen	3.0	1.0
Orthophosphate (PO_4)	0.73	1.4
Chloride (Cl)	1,315.0	2,080.0
Sodium (Na)	960.0	1,300.0
Magnesium (Mg)	252.0	185.0
Potassium (K)	780.0	590.0
Calcium (Ca)	1,820.0	250.0
Manganese (Mn)	27.0	2.1
Iron (Fe)	540.0	23.0
Nickel (Ni)	0.6	0.1
Copper (Cu)	0.12	0.3
Zinc (Zn)	21.5	0.4

Source: Nash and McCall, 1995.

Industrial landfills may contain large quantities of hazardous materials, especially heavy metals and solvents. The disposal of mining waste in spoil heaps can also cause serious pollution problems as the leachate is often highly acidic and may contain excessive concentrations of sulphate and various toxic metals.

Liquid waste is often disposed of in surface impoundments and lagoons, applied directly to land, or injected into deep wells.

Surface impoundments are used to store, treat, or dispose of municipal wastewater and sludge, mine and industrial wastewater, and oil and gas brines. Some impoundments are lined to prevent seepage of the liquid fraction of the waste. But most of them dispose of the liquid by discharge to streams or by seepage through the bottom of the impoundment.

Surface spreading of raw sewage and manure to fertilise agricultural lands is a practice dating back to antiquity. Among other liquid wastes applied onto the land are: wastewater, sludge (by-product of treated wastewater), septic tank pumpings, dairy waste products (whey), and polluted surface water. There are three principal methods for surface application of liquid waste: flood (board) irrigation, ridge-and-furrow irrigation, and spray irrigation. Exposure to elements, plants, and microorganisms in the soil can break down the natural organic matter in the wastewater.

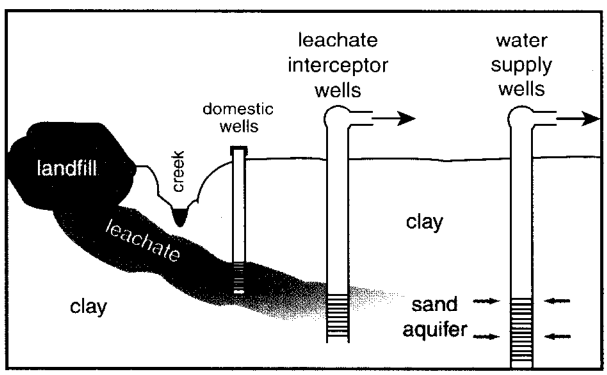
Deep-well injection of waste is practised in industrialised countries for disposal of waste from the chemical, petrochemical, steel, and paper industries and of partially treated wastewater. Deep-well disposal should be considered only after a careful evaluation of geological and hydrological factors, the chemical character of waste, and potential impacts on human health.

The impact of landfill leachate on water supplies in the State of Delaware, USA

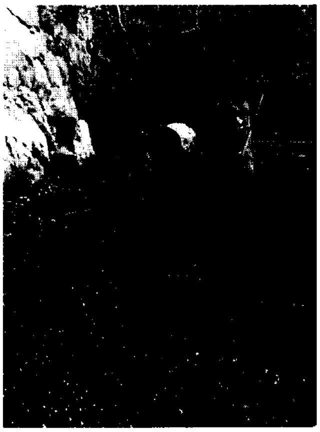
In northern coastal Delaware, liquid and solid industrial waste and municipal refuse were disposed in a 60-acre, 6-9 m deep former sand pit during the 1960s. Unknown to the operators of the landfill, the base of earlier mining operations penetrated the underlying, very low permeability clays and came in contact with extensive inclined layers and stringers of sands confined in the clays. These sand aquifers served as a supply for large capacity (262 l/s) industrial and municipal well fields at a distance of 1,100 m to the south of the landfill.

In 1973, domestic wells just to the south of the landfill detected high concentrations of leachate. In order to intercept this leachate flowing toward 45-60 m deep wells in the well fields, it was necessary to reduce withdrawals from the wells to slow down the flow of this very potent leachate. A barrier of interceptor wells was installed between the landfill and the pumping wells, all of this considerably reducing the ability of a local water supply utility to supply potable water to the community.

The combined pumping of the interceptor wells and the water supply wells resulted in lowering water levels as much as 11 m below sea level. Economic costs and impacts were on the order of many millions of dollars.



Storage and handling of chemicals



Carelessly discarded barrels containing unused tar rusted through over time, which resulted into a spill in an abandoned quarry in Ireland.

Ground-water pollution resulting from storage and handling of chemicals, fuels, and materials used in manufacturing is a product of industrialisation. In industrial countries storage and transmission of chemicals and fuels is a common occurrence within commercial, industrial, and individual uses. However, even in the less industrialised countries there are often numerous small factories that process food, textiles, and leather or various service industries. And the rate of industrialisation in many developing countries continues at a quick pace.

Potential sources of ground-water pollution include stockpiles of materials at factories, tanks for the storage of chemicals and fuels and pipelines used for their transmission, and spills during handling and transport of chemicals. Most common potential pollutants are petroleum products, organic chemicals, acids, and heavy metals.

The worst polluters usually are not the largest industries, which normally have good controls on handling chemicals,but small industries processing leather, metals, and other materials and small service industries, e.g. metal and electroplating workshops, dry cleaners, printers, and vehicle repair shops and petrol stations. All these industries temporarily store, handle, and transfer considerable quantities of potentially toxic pollutants and their housekeeping practices in handling and transferring materials very often are poor.

Accidents during transport of chemicals are inevitable and the resulting spills must be immediately cleaned up by experienced and well-trained crews with the proper equipment before the chemicals soak into the soil and pollute ground water.

Chemicals and fuels are routinely stored in underground tanks at industrial facilities and petrol stations. Underground tanks can leak through holes either in the tank itself or in associated piping. The piping appears to be more vulnerable. The potential of these tanks to leak increases with age and older tanks have to be replaced, usually at a considerable expense. Underground tanks should be routinely tested for leaks.

Petroleum products, agrochemicals, and other chemicals are also stored in above-ground tanks. These tanks present substantially lower pollution risk than underground tanks because they can be inspected for corrosion and leaks from the outside. Installation of containment structures under and around the tanks helps reduce the risk of pollution from sudden ruptures or spills.

Pipelines are used for transmission of petroleum products, gas, ammonia, and other liquids. Although they are designed to retain their contents, many pipelines leak to a greater or lesser extent.

Spills of chemicals and hazardous materials may result from accidents involving tank trucks and railroad cars. Such spills normally are reported to the authorities. More dangerous are the unreported, intentional spills when hazardous liquids are discharged onto the ground illegally rather than being transported to collection facilities.

Agricultural activities

Prior to the 1940s the impact of agriculture on ground water was at a small scale and tended to be localised, either in the vicinity of individual farm wells or perhaps the wells of smaller towns. Fertilisation of crops was accomplished by manual and machine spreading of animal manure, primarily solid, and this loading of the land with nitrogenous substances was actually quite light. Crops yields were relatively low because there simply was not sufficient fertiliser to satisfy large crops. Much agricultural activity was devoted to only one crop per year.

Over the past five decades there has been a radical evolution in agricultural practices all over the world. The intensification of production from agricultural lands has been sustained by new plowing techniques, modernisation of equipment, application of ever-increasing quantities of inorganic fertilisers, introduction of a wide spectrum of synthetic pesticides, and increased irrigation efficiency. These changes were initiated in the industrialised countries during the 1950s and 1960s and have now spread to many developing countries.

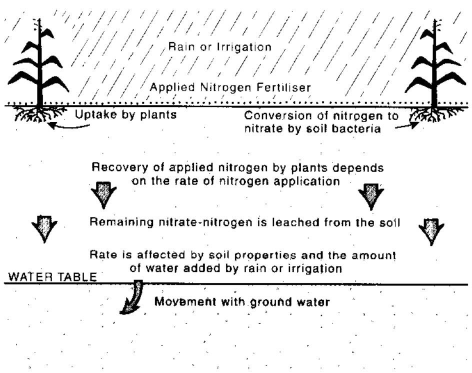
Modernisation of agriculture brought fields into use that had been barren before, increased productivity, and brought multiple crops per year. The result, in many areas, has been ground-water pollution by fertilisers and pesticides, conversion of arable land into near deserts, salinisation of agricultural soils, and raising of water tables in an effort to make former lands very poor in crop yield more productive. Additionally, driving much of the agricultural effort were economic interests that did not foresee the impact of overfertilisation upon ground water and the overall environment.

Agricultural activities are the largest sources of elevated nitrate concentrations in ground water. Since the early 1950s, inorganic fertilisers became more available and less costly in all parts of the world. Unfortunately, the need to produce more food for a growing population required the use of greater and greater amounts of fertiliser, which was often applied in larger amounts than crops can recover.

Nitrogen-based fertilisers release nitrogen, which is the major nutrient for vegetation. Nitrogen is converted by soil bacteria into nitrate, which is highly soluble in water and is not appreciably attracted to soil particles. In natural waters nitrate (NO_3^-) is a minor constituent and seldom reaches concentrations greater than 12 mg/l. However, if large amounts of organic or inorganic fertiliser are applied, the suddenly available nitrate simply cannot be used in its entirety by the crop, and the excess can leach to the water table and rapidly move into the ground water.

An increasing population and consequent increase in demands for meat and poultry resulted in a trend toward confined feeding of livestock. Large-scale livestock and poultry production in confined areas has resulted in intense local pollution of ground water and of domestic and farm water supply wells.The impact is greater where there are inadequately designed and operated animal waste storage facilities and when the animal wastes are spread on the land in the more readily soluble liquid form (animal

Even manual application of pesticides, as practised in many developing countries (such as in Vietnam in rice paddies), can contribute to ground-water pollution, if done indiscriminately.



Some of the nitrate released from fertilisers is retained by crops and soil particles and some is leached from the soil by irrigation water or rain and carried into ground water, contributing thus to its pollution. The leaching of nitrate is dependent on soil and aquifer characteristics, cropping regime, and irrigation scheduling.

In terms of areal extent, agriculture is one of the most widespread human activites that can effect ground-water quality.

feces and urine) in an effort to dispose of these wastes.

More than 300 pesticides are used in agriculture today to diminish the impact of insects and weeds upon crops, and many of them are toxic at very low levels. Pesticides, in terms of mobility, are categorised as ranging from immobile to extremely mobile. Natural soil processes can remove or "tie up"many pesticides; yet others, especially those applied to excessively drained soils, readily percolate into the ground water beneath agricultural lands and produce pollution. Once in ground water, pesticides may persist for long periods of time.

Generally, most pesticide mixing operations occur near wells. Also, many farmers do not realise that the washing out of tanker spray trucks near these wells is seriously impacting the water that they will later drink. Eventually they notice the pesticide smell and cease use of the wells, but not before the health of those using the wells is impacted.Compounding the problem is the improper disposal of partially used containers of pesticides. Burial is not an answer; it only places the pesticides closer to the water table.

In many regions, farmers depend on irrigation water as a sole or supplemental source of water for agricultural production. Irrigation of agricultural lands can result in an increased soil salinity such that crops will gradually decline in production. This is made even worse if the irrigation rate is low. Insufficient irrigation water tends to concentrate salts at a single depth. If the soil is well drained, the salty irrigation water will move deeper each growing season until it reaches the ground water, which then begins to increase in salinity. This rise in salinity of the ground water results in the application of a more mineralised irrigation water to subsequent crops.

In many semi-arid areas, expansion of irrigation has led to land degradation due to twin problems of waterlogging and salinity. Waterlogging can be prevented or corrected by reducing excess water inputs and increasing natural drainage capacity. Salinity can be controlled by improved irrigation scheduling and surface water/ground-water conjunctive use. In 1993, the Food and Agriculture Organization reported that more than one third of the world's irrigated lands are affected by soil salinity.

Extent of agricultural pollution

The following few examples from various regions of the world may help appreciate better the magnitude of ground-water pollution by agricultural practices.

In the Yucatan peninsula of Mexico, nitrate concentrations in a karstic carbonate terrane have risen up to about 160 mg/l, mainly as a result of the increased pork production and use of fertilisers. In two karst aquifers of western Cuba, nitrate increased 4 to 8 times just ten years after intensive agricultural practices started. Studies by the British Geological Survey have shown that shallow ground water in the Jaffna and Kalpitiya peninsulas in northern Sri Lanka contains locally between 133 and 221 mg/l of nitrate.

In Europe, pore-water profiling of the unsaturated zone of the British Chalk indicated that large quantities of nitrate (88-308 mg/l) leached from arable land are moving to the water table. Nitrate concentrations in the agricultural regions Celjska, Pomurska, and Mariburska of Slovenia reached more than 100 mg/l locally.

In the United States, three quarters of the ground-water supply in the State of California have been degraded by nitrates, pesticides, and salinity from intensive agricultural production. Ethylene dibromide applied for pest control to well-drained, sandy soils in northwest Florida, leached into the underlying Floridan aquifer. The drinking water standard of 0.02 μg/l was often exceeded 60 to 400 times.

In Western Australia, clearing natural vegetation for agriculture resulted in increased recharge to ground water and rising water levels that leached salinity from soils overlying the aquifers. About 1.8 million hectares are affected, with a doubling expected in 25 years.

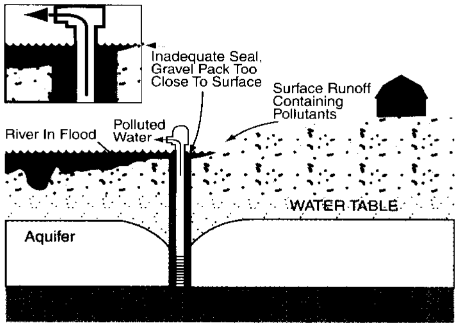
Domestic sources

Ground-water pollution may be caused by wells supplying water to individual households and by household sanitation facilities.

Properly constructed water wells are not normally sources of ground-water pollution. However, if a casing has been corroded or ruptured or if the surface casing is not adequately sealed, wells can serve as a means for transmission of pollutants from the land surface to the aquifer or from one aquifer to another. Many domestic wells are polluted in this way by polluted surface runoff or by effluent from a too-closely located sanitation unit.

Improperly abandoned domestic wells are common potential sources of pollution, especially in urban and suburban areas. In the years before there were community water supply systems, most people in the cities relied on private wells to provide their drinking water. As the areas served by public water systems expanded, these domestic wells were often abandoned without being properly sealed. These old, often long forgotten and built over wells serve as conduits through which pollutants can enter an aquifer or migrate freely from one aquifer to another. Also, an open abandoned well frequently becomes a convenient receptacle for household garbage, a variety of liquids, or dead animals.

On-site sanitation units, such as septic systems, cesspools, and latrines, are designed to discharge domestic wastewater into the subsurface above the water table in residential areas without, or with partial, sewerage system. Although each unit can make an insignificant contribution to ground-water pollution, the sheer number of such units, their widespread use in unsewered areas, and large volumes of wastewater discharged, makes them serious pollution sources. If properly located, designed, and maintained, the on-site systems do not contribute much to ground-water pollution. However, if they are densely spaced, their discharge exceeds the capacity of the soil to assimilate pollutants, and ground water becomes polluted, especially by high concentrations of nitrate.



Water wells not protected by adequate seal can be polluted by surface runoff entering the well along the casing.

On-site sanitation units present a greater risk under some hydrogeological conditions, such as karstic limestones or fractured rocks with a thin or no soil cover or in areas of shallow water table, where bacteria and viruses can directly migrate to underlying aquifers.

Improvements in sanitation are urgently needed in many developing countries. It has become an accepted practice that on-site sanitation can provide adequate service for the disposal of human waste in rural areas, villages, small towns, and even parts of larger urban areas at much lower cost than sewerage systems. As a result of this practice, sooner or later, an enormous expansion of excrement disposal into the ground will lead to widespread ground-water pollution.

The pollution of ground-water supplies by on-site sanitation units has already been reported from many countries of Africa, Asia, and Latin America, and it is particularly severe for communities on low-lying Atlantic and Pacific islands.

High density of LOFLOS (low-flush on-site sanitation) can cause widespread pollution by nitrate.

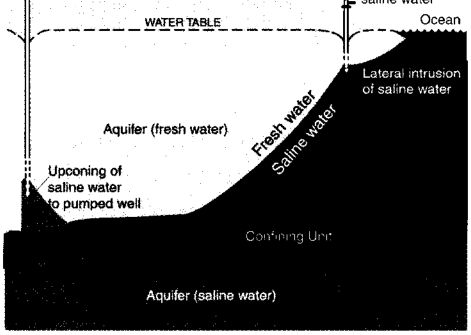
Ground-water development

Over-exploiting ground water can have serious consequences for ground-water quality.

Ground-water pollution can also result from the uncontrolled development and abstraction of ground water. The encroachment of saline water is an ever-present threat to ground-water supplies developed in coastal aquifers, where under natural conditions fresh ground water is delicately balanced on top of denser sea water. Uncontrolled abstraction of ground water can disturb this natural balance and result into movement of sea water into an aquifer.

Due to the lack of adequate amounts of fresh surface water, the communities and farmers in coastal areas have turned to ground-water resources to satisfy the increasing demands for water supply and irrigation. Wells in coastal areas were pumped longer and for greater quantities and were progressively deepened. As the community grew in population and industrialisation, often with later tourism, and as the irrigated agriculture expanded, the demands on the ground-water system increased to a point where the limits of the system were exceeded. This limit is one in which the position of the fresh/salt water interface began to shift laterally and vertically, such that wells began to produce gradually saline water.

The phenomenon of salt-water intrusion is well known and understood, but somewhat difficult to predict in terms of precise location and the level of impact.Such intrusion is simply not due just to ground-water extraction from wells, but can also be attributable, in part, to paving over land surface and diminishing recharge to coastal aquifers. Coastal area land use and water management are critical to determining the balance between maintaining a sustainable potable water supply and the deterioration of aquifer water quality.



Fresh ground water can be polluted by the upward advance of saline water of geological origin from deep aquifers and by an invasion of sea water in coastal aquifers.

Some of the earliest investigations of saline water encroachment occurred in the coastal areas of the Netherlands and Germany, which resulted into development of a theory explaining the causes and control of saline water intrusion (DeBreuck, 1991).

Pollution of ground water by sea water has occurred practically in all populated coastal areas of the world. And many large coastal cities (e.g. Bangkok, Jakarta, Manila, and Miami) have experienced serious problems with salt-water intrusion, which often results in the loss of important water supplies. Over-exploitation of ground water and resulting salt-water intrusion is especially critical problem on small oceanic islands where ground water is limited and is the only source of drinking water.

Yet, ground-water development in areas far from the sea has also caused aquifers and wells to become salty. Many inland areas are underlain at depth by saline water contained within the rocks. This water has no relation to modern seas, but possibly represents water trapped in the original sediments of ancient seas that have not been flushed by relatively modern recharge. Such water, when wells are constructed to depths that reach near to the top of saline aquifers, rises vertically through "upconing." These problems are particularly frequent in semi-arid and arid regions where fresh water is usually quite limited and people depend on deep wells for water supply.

Ground-water protection

Ground water is the largest source of fresh water in the world. During the past few decades there has been an immense increase in ground-water development and utilisation, especially in developing countries. In view of the diverse uses of ground water, it is essential to keep it free from any kind of pollution. However, the real danger is not pollution but the ignorance of pollution problems.

While ground water is less vulnerable to pollution than surface water, the consequences of ground-water pollution last far longer than those of surface water pollution. Pollution of ground water is not easily noticed and in many instances the pollution is not detected until pollutants actually appear in drinking water supplies, by which time the pollution may have affected a large area.

Although it cannot be completely eliminated, ground-water pollution can be minimised or corrected. But before appropriate protection measures can be designed and implemented, ground-water pollution and its sources must be assessed and the vulnerability of the environment to pollution evaluated.

A systematical, detailed inventory of the existing and potential pollution sources must be undertaken to evaluate potential threats to ground-water quality. The extent of existing ground-water pollution should be determined, especially around suspected sources of pollution. One of the means to accomplish this is monitoring. Monitoring wells can be installed to discover ground-water pollution from a given activity, detect the extent of pollution, and provide an advance warning of the polluted water approaching important sources of water supply.

The assessment of vulnerability of ground water to pollution is based on the assumption that the physical environment may provide some degree of protection against the natural and anthropogenic impacts. The vulnerability is dependent on a number of factors, including soil type, characteristics and thickness of materials in the unsaturated zone, depth to ground water, aquifer type and permeability, and the amount of recharge to the aquifer.

There are basically two approaches in dealing with ground-water pollution problems: to handle the pollution after it has occurred or to prevent new occurrences.

Many methods are available to remedy pollution of ground water. In favourable natural conditions, natural purification processes can help attenuate polluted water entering the subsurface and reduce pollution to an acceptable level. Many remedial methods and innovative technologies have been developed during the last two decades to help clean the polluted ground water. However, cleanup is difficult and expensive, and generally requires long periods of time. Therefore, a major effort should be directed toward preventing pollution from occurring. The cost of ground-water protection through prevention is generally much smaller than the cost of correcting the pollution after it is found.

A successful ground-water protection program must include a combination of three basic alternatives: prevention, remediation by natural attenuation, and remediation technology.

Pupils at the Bushy Park School near Port Elizabeth, South Africa, enjoy fresh water from a flowing well.

Natural attenuation

The earth materials may act as natural filters to screen out some pollutants.

Long before man populated the earth, nature was producing moderate amounts of what are now called polluting substances. Because these pollutants have been produced for millions of years and life on earth did not disappear due to a continuous pollution buildup, it is apparent that nature has its own purification processes. These processes are called ***natural attenuation***.

For a number of years investigators and researchers have observed that as polluted ground water travels through the soil and rock, there is a tendency for this water to improve in quality with distance and with time. Yet this improvement is not the same for all soil and rock types. Additionally, different polluting substances are cleansed to different levels. And controlling local land and water uses is often needed to give the natural processes the chance to work.

The potential for natural attenuation is limited and varies from place to place. It is obvious that if there is nothing in the soil or rock that will act upon the ground-water pollutants, there will be no natural attenuation of the ground water. Pure silica sands or fractured but non-reactive rocks are unlikely to play a role in natural attenuation, except that dilution and dispersion of pollutants will take place.

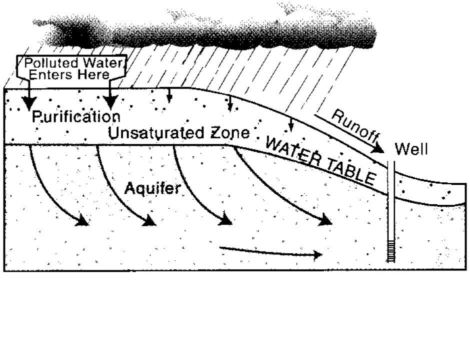
Soils that contain clays, iron oxides, calcium carbonate, and organic matter, among other substances, tend to be quite reactive with pollutants. Similarly, sands with such materials often act upon pollutants and reduce them to levels that, while not totally acceptable for drinking water, do not pose an imminent hazard to public health and the environment. If such earth materials and associated ground water contain naturally-occurring microorganisms that can biologically "lock up" or break down fuels and solvents into less harmful substances, then the threat is lessened even further.

Acidic heavy-metal bearing waters can be neutralised by flowing through rocks such as limestones or sediments with a high calcium carbonate content. By such means, the metals are precipitated out of the ground water.

The reduction in pollutant content of ground water is due to a number of processes. The unsaturated zone has the greatest variety of processes, such as dispersion, filtration, volatilisation, sorption, and biological actions. Fewer processes take place in the aquifer where dilution and solution are the most effective in the attenuation of pollutants.

Considering the often extreme economic cost of ground-water remediation, research has been conducted in many countries to determine what precisely occurs during the process of natural attenuation. The result has been that natural attenuation has become an accepted alternative method for cleaning polluted shallow aquifers, although the processes often have to be enhanced by the introduction of additional microorganisms or nutrients.

One of the advantages of natural attenuation is that it does not move pollutants from one place to another (like most remedial methods), but that it results in real reduction in pollutant mass. However, caution must be exercised to avoid overusing natural attenuation as a remedy. Clearly, some sites may be effectively cleaned up by natural attenuation processes, but others still need the application of remedial technology.



Natural purification of polluted water by physical, chemical, and biological processes is most effective in the unsaturated zone.

Prevention

Given the importance of ground water as a source of drinking water for so many communities and individuals and the cost and difficulty of cleaning up polluted water, the best way to guarantee continued supplies of clean ground water is to prevent pollution. There are a number of alternatives available to accomplish that.

Legislation

Almost each nation has some kind of a basic Water Act, which covers all water resources, applicable to its physical, political, and cultural situation. Special provisions for ground-water protection may be incorporated within this Act or may be added later. National water laws generally provide only an initial framework for the control of ground-water pollution and have to be complemented by statutes authorising programs relevant to ground-water protection or by state/province or local regulations. Detailed national regulations for ground-water protection cannot exist because what is best for a given situation depends on local conditions.

Regulatory options

A wide variety of regulatory mechanisms can be used to prevent pollution from occurring.

One of the most powerful regulatory tools are land use controls, which enable local governments to address important aspects of pollution prevention that are not adequately covered by national or state regulations. However, land use regulations can control the type, location, and intensity of new land uses only; they do not affect the existing ones.

Prevention of ground-water pollution involves in the first place the control or elimination of pollution sources.

This can be achieved by:

(a) better product control and restricting or banning harmful products;

(b) issuing conditional use permits for potentially polluting activities and design and operating standards for facilities handling or disposing waste and hazardous materials; and

(c) conducting mandatory training for operators of facilities that have a potential to pollute ground water and inspecting such facilities regularly.

An important aspect of any regulatory program is the designation of lead agencies responsible for enforcing the laws and regulations and for ensuring compliance with standards or ordinances. Enforcement of standards and regulations is perhaps the most difficult task of these agencies. Two alternative approaches can be used to encourage regulatory compliance: penalties (fines, taxes, loss of licenses) and incentives (tax credits, compensation, grants).

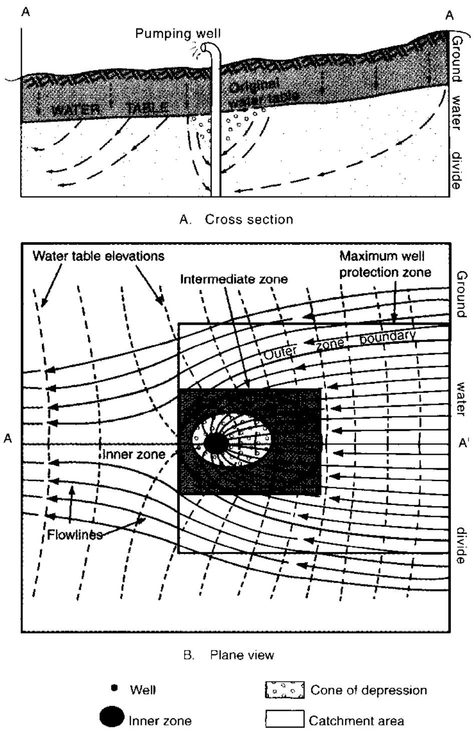
"Prevention is better than cure."
Ancient proverb

Methods for control of some pollution sources

SOURCE	CONTROL METHOD
Landfills	Regulation of siting, construction, operation, and closure. Monitoring.
Underground storage tanks	Periodic inspection and pressure testing. Monitoring.
Hazardous wastespills, leaks, or improper disposal	"Paper trace" of hazardous materials. Storage regulations. Heavy fines. Mandatory inspection of transportation equipment. Spill removal.
Fertilisers and pesticides	Nutrient management to meet crop needs. Minimising pesticide needs or application ban. Regulation of disposal of used containers.
Septic systems	Regulation of siting and installation. Required periodic inspection. Licensing installers.

In addition to regulations controlling pollution sources, regulatory actions also are needed for the protection of drinking water supplies and aquifers. Regulations can be issued to govern the siting, construction, and abandonment of water wells and to ensure proper well construction by establishing a program for licensing well drillers.

Important sources of drinking water can be protected by delineating protection zones, in which potentially polluting uses and activities are controlled. Ideally, the protection zone would include the entire catchment contributing ground water to the source. Such a protection zone would be complex and relatively large, placing severe economic burden on a community. In practice, the catchment area is usually divided into two or three zones, and the most severe restrictions are applied only to the zone close to the source.



Ground-water source protection zones usually consist of the inner zone (a radius of up to 150 m from the source), intermediate zone, and outer zone (covering the entire catchment area).

Aquifers can be protected by setting aside special ground-water protection areas, such as the most vulnerable areas or critical recharge areas, in which legal constraints are placed on potentially polluting activities.

Non-regulatory actions

Voluntary management practices, waste reduction, "housekeeping" practices, and public education and information are equally important to effective prevention efforts and can commonly supplement regulatory programs.

Managers or operators of facilities producing or handling chemicals and hazardous substances can issue guidelines for employees how to handle and store the potentially polluting substances and can train the staff about prevention measures so that their actions would not result into introducing pollutants into ground water.

The impact of agricultural practices could be reduced by informing and educating farmers about voluntary actions through which they can better manage animal waste, apply fertilisers and pesticides according to plant needs, and properly schedule irrigation.

Individuals can help by improving their housekeeping practices, by learning how to properly dispose of household products containing hazardous substances, and by making sure that their wells are well maintained and not situated too close to potential pollution sources, and that stagnant water is not allowed to pond close to the top of the well.

Very important are those actions that lead to minimising the input of pollutants: waste reduction through recycling, emergency spill response plan, and public education program that would help individuals and land managers better understand the relationship of land use activities to ground-water pollution.

Cleanup

Once polluted, ground water is very difficult and very costly to clean. When ground-water pollution occurs, the two most important factors for successful cleanup are responsiveness and appropriate technology. The faster the response following detection of pollutants in ground water, the shorter the distance that a pollutant plume will have moved and the more successful the remediation or cleanup. At the same time, selection of a cleanup technology or technologies appropriate to the nature of the pollutants and the site hydrogeology is very critical.

During the 1980s methods of restoring ground-water quality by implementing various types of remedial measures were developed. There are three broad categories of cleanup technologies: remove or isolate the source, pump-and-treat the ground water, and treat the ground water in-situ (Boulding, 1996).

Source control is the first step in the remediation of ground water, which is taken to prevent the continuing release of pollutants to the subsurface or to ground water. If it is economically or technically feasible, the source can be excavated and removed. Various controls can be used to isolate the source from infiltrating water to slow down pollutant production: surface drainage diversion, construction of low-permeability covers or caps above the source, and ground-water flow diversion. Physical containment can include encapsulation of a source or vitrification (fusion of soils and wastes into a glassy monolith).

Source containment can be achieved by construction of physical or hydraulic barriers around the source. Slurry walls have been in use for this purpose for many years. They are constructed by continuous-trench excavation down to and into a horizon of lesser permeability, and at the same time placing a bentonite (water-expansive clay derived from volcanic ash) slurry in the trench as it proceeds forward. The slurry walls are installed upgradient (to stop the inflow of ground water), downgradient (to contain the spread of a pollutant plume), or completely around pollutant sources to lessen further pollutant movement until more extensive cleanup can occur.

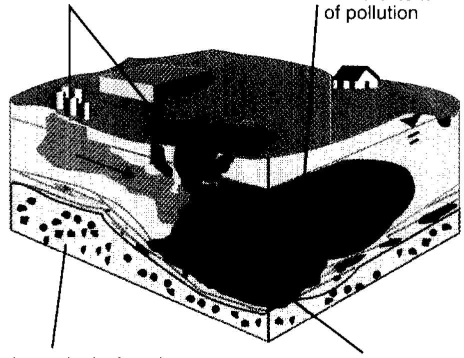
Hydraulic containment relies on ground-water pumping on a single well or a line of well points to change the hydraulic gradient to divert ground water or to withdraw polluted water.

The most widely used approach to ground-water remediation is extraction of the polluted water and its treatment at the surface, referred to as the pump-and-treat technology, which was thought to be the answer for cleaning up a polluted site. It is now known that this method, although very important, is not the complete answer. Pump-and-treat is often the first stage of cleanup, primarily to remove the largest portion of the pollutant mass. However, some substances, such as dense non-aqueous phase liquids (DNAPLs), tend to sink to the bottom of an aquifer and also tend to attach themselves to the finer sediment particles. In these cases, long-term pumping may give the illusion that the cleanup process is quite successful. However, pollutants are never quite removed and continue to be released in the ground water. When

Cleanup costs

Cleanup of polluted sites can be time-consuming and extremely expensive. In 1980, U.S. Congress appropriated $1.6 billion for the cleanup of old hazardous waste sites (the so-called Superfund law). In 1986 the Superfund was expanded and additional $8.5 billion appropriated. And in 1998, billions of dollars later, only 162 of the 1,350 designated Superfund sites were cleaned up. An average cleanup cost is more than $20 million per location.

In Denmark, the Legislature granted Dkk 500 million, for the period 1991-1993, to clean old waste disposal sites. However, costs of Dkk 10-20 billion have been estimated for cleanup of all registered disposals in the country.



Selection and design of an appropriate cleanup technology depends on the site hydrogeology; location and characteristics of pollution sources; types, concentrations, and distribution of pollutants; and potential for ground-water restoration.

Cleanup in Europe

In Europe, more than $5 billion per year is spent to reverse the current damage done by ground-water pollution and to prevent ground-water pollution.

Reducing the pollutant mass makes cleanup easier. A prompt response to a burst-pipe accident in the State of Minnesota, USA, resulted into a 76%-recovery of the spilled oil.

pumps are turned off, ground-water levels rise and move upward through the still polluted soils. The result is a new "release" of pollutants.

With the limitations of pump-and-treat in mind, more appropriate in-situ technologies were developed. Among these are soil flushing, vapor extraction, steam injection, and biodegradation.

Soil flushing is the introduction of water or water mixed with additives onto or beneath the surface to mobilise and push pollutants toward recovery wells where the pollutants can be extracted and treated.

Many volatile compounds are difficult to remove from ground water by simple pumping of recovery wells, because a large portion of the pollutant may be contained in the unsaturated zone. A technology that has been successful to remove such compounds is the soil vapor extraction. This process uses a series of wells installed throughout the polluted area that, instead of pumping water, are designed to pump air through the use of vacuum blowers. Air, moving through the unsaturated zone, extracts volatile pollutants from the soil.

Some organic volatile and semi-volatile wastes can be extracted from the polluted soil and ground water by injecting steam under high pressure through wells into the unsaturated zone or into the aquifer itself.

At many gasoline-polluted sites it was observed that high alkalinity and large amounts of carbon dioxide were present in the ground water. This was attributed to the action of natural microorganisms (bacteria) using the petroleum-related compounds as energy sources. In the process of "eating" these substances the bacteria generate wastes, including carbon dioxide.With this in mind, scientists realised that if they could force the bacteria to metabolise more of the pollutant or if there were more bacteria in the soil and ground water, ground-water cleanup would be more effective and faster.

In-situ biodegradation uses microorganisms to convert pollutants to less harmful forms. This method has the added benefit that the polluted soil and ground water do not need to be disturbed. Electron acceptors (oxygen and nitrate), nutrients, and other substances can be added to the soil and aquifer by means of injection wells to stimulate biodegradation of pollutants. Bioventing delivers oxygen to soil. Air sparging is the similar process except that air is injected below the water table.

The difficulty of cleanup depends on several factors: pollutant characteristics, hydrogeological characteristics of the polluted site, mass of pollutant released, size of the source area, and the length of time the pollutant remained in the subsurface before cleanup. The length of time required for cleanup generally increases with the amount of pollutant mass and the size of the source area.

Sometimes only one of the above technologies is necessary for cleanup of soil and ground-water pollutants from a site. In other cases, a sequence of cleanup technologies is required. Technologies to clean up ground water and associated rocks, sediments, and soils are constantly being developed and improved. There is likely to be much additional progress in technology innovations.

In all cases, ground-water monitoring of the aquifer and the sampling of gases and waters from the soil and the unsaturated zone are critical to the evaluation of the effectiveness of the cleanup technologies being used. Additionally, no cleanup effort will be successful if the site geology, hydrology, and geochemical nature are not thoroughly understood.

Sources of information

Boulding J.R. (ed.) (1996) ***EPA environmental engineering sourcebook.*** Ann Arbor Press, Inc., Chelsea, MI, USA, 404 p.

Candela L. and Aureli A. (eds.) (1998) ***Agricultural threats to groundwater quality.*** UNESCO-IHP, IAMZ-CIHEAM, and Technical University of Catalonia, Zaragoza, Spain, 251 p.

Clarke R., Lawrence A., and Foster S. (1996) ***Groundwater: a threatened resource.*** UNEP Environmental Library No. 15, UN Environment Programme, Nairobi, Kenya, 36 p.

Daly D. (1985) ***Groundwater quality and pollution.*** Geological Survey of Ireland, Information Circular 85/1, 25 p.

DeBreuck E. (ed.) (1991) ***Hydrogeology of salt water intrusion.*** Verlag Heinz Heise, Hannover, Germany, International Contributions to Hydrogeology, Volume 11, 422 p.

Lawrence A. and Foster S. (1996) ***Characterisation and assessment of groundwater quality concerns in Asia-Pacific region.*** UNEP/DEIA/AR.96-1, UN Environment Programme, Nairobi, Kenya, 102 p.

Moody D.W. (1990) 'Groundwater contamination in the United States.' Journal of Soil and Water Conservation, v. 45, no. 2, p. 170-179.

Nace R.L. (ed.) (1971) ***Scientific framework of world water balance.*** UNESCO Technical Papers in Hydrology, 7, 27 p.

Nash H. and McCall G.J.H. (eds.) (1995) ***Groundwater quality.*** AGID Special Publication No. 17, Chapman & Hall, London, UK, 204 p.

RIVM and RIZA (1991) ***Sustainable use of groundwater—problems and threats in the European Communities.*** National Institute of Public Health and Environmental Protection (RIVM) and National Institute for Inland Water Management and Waste Water Treatment (RIZA), The Netherlands, 80 p.

Tebbutt T.H.Y. (1983) ***Relationship between natural water quality and health.*** UNESCO Technical Documents in Hydrology, 25 p.

UNESCO (1992) ***Ground water.*** UNESCO Environment and Development Briefs No. 2, 14 p.

UN Food and Agriculture Organization (1993) ***The state of food and agriculture 1993: water policies and agriculture.*** FAO, Rome, Italy.

Vrba J. and Romijn E. (eds.) (1986) ***Impact of agricultural activities on ground water.*** Verlag Heinz Heise, Hannover, Germany, International Contributions to Hydrogeology, Volume 5, 332 p.

World Health Organization (1993) ***Guidelines for drinking water quality.*** WHO, Geneva, Switzerland, 188 p.

Zaporozec A. (1981) 'Ground-water pollution and its sources.' GeoJournal, v. 5, no. 5, p. 457-471.