Background Information

Introduction to Groundwater Hydrology

Groundwater hydrology is the study of the occurrence, movement, and quality of underground water. The field is interdisciplinary, drawing on the subjects of physics, geology, chemistry, soil science, and plant physiology.

Groundwater provides drinking water for half the population of the United States and accounts for about 60% of the water used in mining, irrigation, and raising livestock. Groundwater also contributes significantly to flow in many streams and rivers and influences the distribution of wetland habitats for plants and animals. Since 1950, the nation's use of groundwater has increased from 34 billion to about 80 billion gallons per day in the 1990s. Over the same period, surface-water reservoir capacity increased nearly threefold, but in recent years it has leveled off considerably. With surface-water sources unable to meet demand (particularly in the arid western United States), groundwater becomes an increasingly vital resource.

Abundance and Circulation of Water on Earth

Looking at photos of the Earth taken from space, one sees that blue oceans, white polar caps, and clouds dwarf the continental landmasses. About 70% of the planet is covered with water. However, nearly all of the estimated 326 million cubic miles of water on Earth is in the oceans or ice caps and is largely unusable by humans. Table 1 shows a breakdown of the world's total water supply.

Table 1: Earth's Total Water Supply

Water Source	Water Volume (cubic miles)	Percent of Total Water
Oceans	317,000,000	97.24
Ice caps, glaciers	7,000,000	2.14
Groundwater	2,000,000	0.61
Fresh-water lakes	30,000	0.009
Inland seas	25,000	0.008
Soil moisture	16,000	0.005
Atmosphere	3,100	0.001
Rivers	300	0.0001

Adapted from U.S. Geological Survey, http://ga.water.usgs.gov/edu/earthwherewater.html (accessed February 12, 2001).

Water moves constantly between those sources most useful to humans. The sun heats bodies of water, causing water to evaporate and enter the atmosphere. As they breathe, plants and animals also release large quantities of water vapor through a process called transpiration. As all this moisture rises, it cools and condenses into clouds, which then release water in the form of rain, sleet, or snow. This precipitation falls to the ground and eventually becomes part of surface flow or infiltrates into the ground, thus beginning its journey back to the ocean. Some water will be taken up into the atmosphere again along the way through evaporation or transpiration. This process, known as the hydrologic cycle, is illustrated in Figure 1.

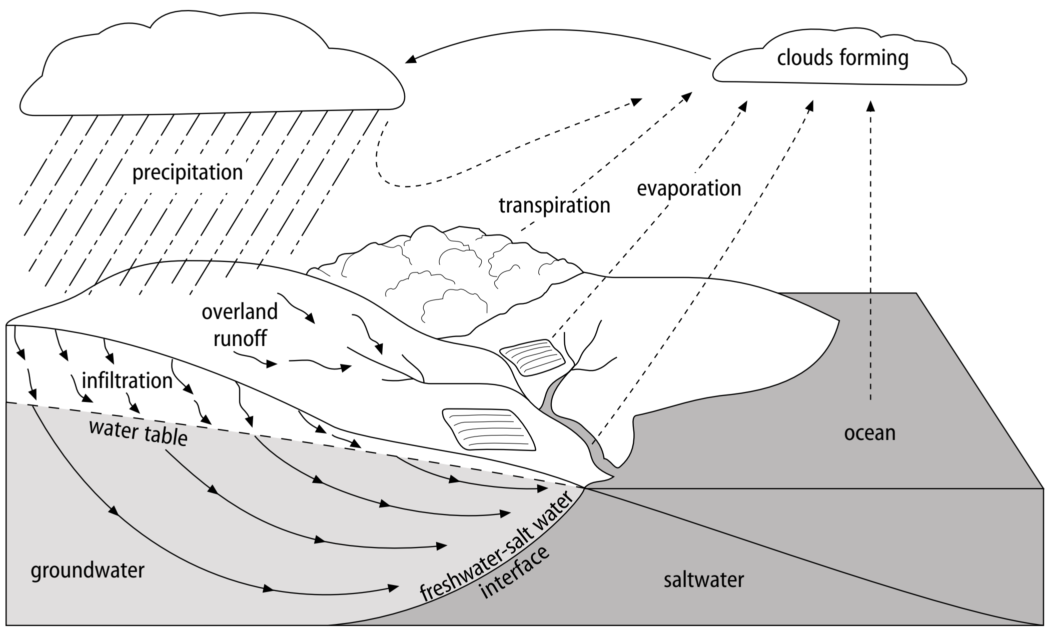

Figure 1: The hydrologic cycle
(Adapted from R.C. Heath, Basic Ground-Water Hydrology, *1989.)*

Occurrence of Groundwater

According to the U.S. Geological Survey's *Basic Ground-Water Hydrology*, about 14% of all fresh water is groundwater—an amount that far outweighs the water in all the lakes and rivers combined. If we disregard the water locked up in glacial ice, then 94% of the Earth's fresh water is groundwater. Because groundwater is mostly hidden from view, its occurrence is the source of numerous misconceptions. One popular misconception is that groundwater can be found only by specially trained experts who know where to look for it. In fact, most of the shallow surface layers of the Earth are saturated with water below a certain depth. A person digging just about anywhere will eventually strike water, although the quality and yield of that water will differ with location.

Another common misconception is the idea that groundwater flows in underground rivers or "veins." Groundwater actually occupies innumerable pores and cracks, many of which are invisible to the unaided eye, in the seemingly solid rock beneath our feet. The total volume of these tiny voids far exceeds the volume of all the caverns of the Earth. The United States Geological Survey estimates that the total volume of subsurface openings beneath the United States alone is about 125,000 cubic miles. If these openings formed a continuous cave beneath the surface of the entire United States, its average height would be 186 feet.

Groundwater occurs in either unconsolidated, sediment-like deposits or consolidated rock, usually referred to as bedrock. Unconsolidated deposits vary in thickness from less than an inch near bedrock outcroppings to many thousands of feet in deep basins or river deltas. Solid bedrock underlies unconsolidated deposits everywhere on the planet.

Most unconsolidated deposits originate from the erosion of consolidated rock. These deposits consist of rocks and minerals that range in decreasing grain size from gravel, sand, and silt to clay. Even tightly packed granular material contains a considerable amount of pore space, as shown in Figure 2. Since groundwater fills in the pore space, we can see why unconsolidated deposits are very important reservoirs for groundwater.

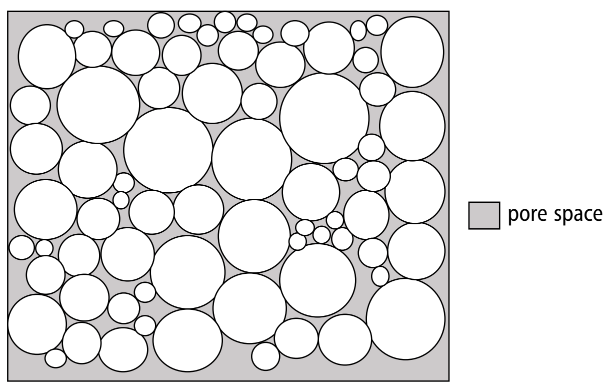

Figure 2: Pore spaces in a granular material

Infiltration of Water

When precipitation in the form of rain hits the ground, it quickly wets vegetation and other surfaces and then begins to infiltrate the ground. The rate of infiltration will vary, depending on the amount of vegetation, soil type, and the length and duration of rainfall. When rainfall exceeds the rate of infiltration, surface runoff (overland flow) occurs.

As water moves down into the subsurface under the force of gravity, it passes through several zones as shown in Figure 3.

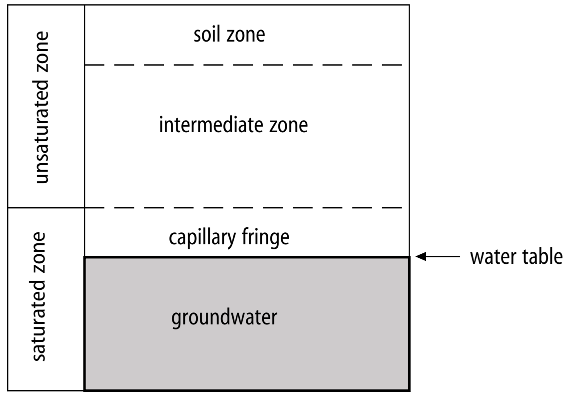

Figure 3: Subsurface water zones (not to scale)

The soil zone extends from the surface to a depth of several inches to several feet. This zone contains tree roots, decaying organic matter, and animal burrows. The churning by living organisms tends to give the soil zone a higher porosity and permeability than underlying zones. An intermediate zone of variable thickness and reduced biological activity usually underlies the soil zone. The pore spaces in these two zones contain both water and air, so together these zones make up what is called the unsaturated zone. At the base of the unsaturated zone lies a narrow subzone (the capillary fringe) where capillary action causes underlying groundwater to rise upward against the pull of gravity. Although pore spaces in the capillary fringe are saturated with water, the water cannot be usefully extracted in a well because the pressure exerted by the water (hydrostatic pressure) is less than atmospheric pressure. Hydrostatic pressure is a measure of the weight of a column of water. You may have felt the effect of hydrostatic pressure if you've scuba dived in the ocean or swam underwater in a deep swimming pool. The depth at which hydrostatic pressure becomes equal to atmospheric pressure is known as the water table. Below the water table, groundwater will spontaneously flow into a dug hole or well. Only water below the water table is properly called groundwater. The combined groundwater zone and capillary fringe is known as the saturated zone.

Depth to Groundwater

The depth of the water table below the surface varies depending on topography and climate. In humid or semiarid areas, the water table is usually anywhere from 0 to 50 feet below ground surface. In some desert environments, the water table may be hundreds of feet below the surface.

As shown in Figure 4, the surface of the water table generally conforms to ground surface topography; however, it lies at a greater depth under hills than under valleys. In general, we can view swamps, lakes, and perennial streams as areas where the water table intersects the ground surface. The depth to the water table may also vary seasonally. During months of high rainfall, the water table can rise high enough to flood low-lying areas, including basements, that are otherwise dry.

In any region, the shallow subsurface may contain isolated beds of impermeable material that can trap infiltrating water to form what is known as a perched water table. A perched water table may lie dozens of feet above the regional water table.

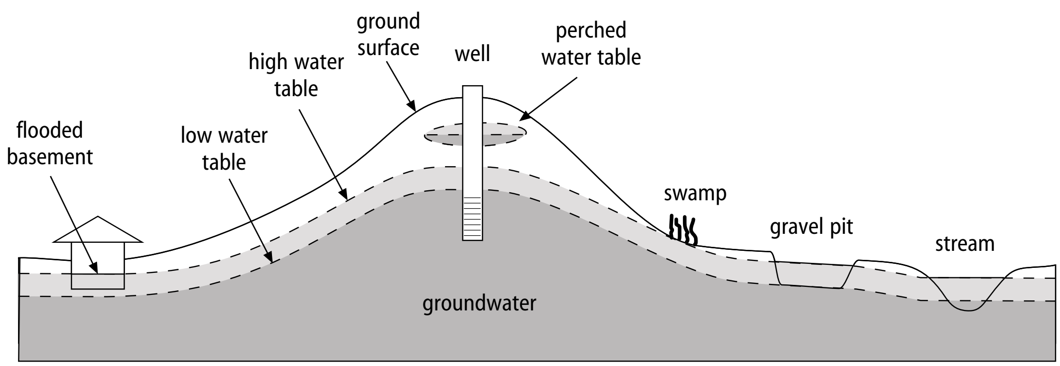

Figure 4: Location and seasonal changes of the water table

Porosity and Permeability

Porosity is the ratio of void spaces in a rock compared with the total volume of the rock. It is expressed as either a decimal fraction or as a percentage. Porosity tells us how much water a rock can contain when saturated. According to the U.S. Geological Survey, porosities can range from 25–50% in soil and loose sand to as little as 0.1% in unfractured granite.

Although porous subsurface formations can hold significant quantities of groundwater, the water is of little use if it is unable to flow readily. Permeability is a measure of the interconnectivity of the pore spaces. Interconnected pores act like tiny conduits or pipes that allow fluids to flow relatively unimpeded. Some materials, like clay or shale, contain a tremendous amount of pore space. However, because clay minerals are flat rather than rounded, the pores are very poorly connected.

The permeability or hydraulic conductivity of a rock is a quantitative measure of how fast groundwater can move through it and is usually expressed in meters or feet per day. Table 2 shows some typical porosities and hydraulic conductivities for common earth materials; however, permeabilities can vary by several orders of magnitude depending on grain size, amount of fracturing, and degree of consolidation of the rock.

Table 2: Typical Porosity and Hydraulic Conductivity for Selected Earth Materials

Material	Porosity (%)	Hydraulic Conductivity (feet/day)
Clay/shale	50	0.00001
Sand	25	20
Gravel	20	500
Limestone	20	1
Sandstone	11	0.1
Granite	0.1	0.0001
Basalt (lava rock)	11	10

Adapted from R.C. Heath, *Basic Ground-Water Hydrology,* 1989.

Geologic units that have sufficient porosity and hydraulic conductivity to allow groundwater to be efficiently extracted for human use are called aquifers. Aquicludes, aquitards, and confining beds are units with low hydraulic conductivity that prevent or impede the flow of groundwater.

Types of Aquifers

Groundwater occurs in two principal types of aquifers, as illustrated in Figure 5. An unconfined aquifer is one that is only partly filled with water, so that the upper boundary of the saturated zone is free to rise and fall. The water level in wells drilled into an unconfined aquifer usually corresponds to the top of the water table. For this reason, unconfined aquifers are also known as water-table aquifers.

When an aquifer is completely filled with water and lies under a confining bed, the aquifer is said to be confined. Groundwater in confined aquifers, sometimes called artesian aquifers, is typically at a pressure greater than hydrostatic pressure. Water levels in wells drilled into artesian aquifers are at some level above the top of the aquifer but not necessarily above ground surface level. The water level in an artesian well is called the potentiometric surface; it is the level that the water in the confined aquifer would naturally rise to if it could get past the confining layer. When the water pressure in the aquifer is high enough to force water to the surface, then the well is called a flowing artesian well.

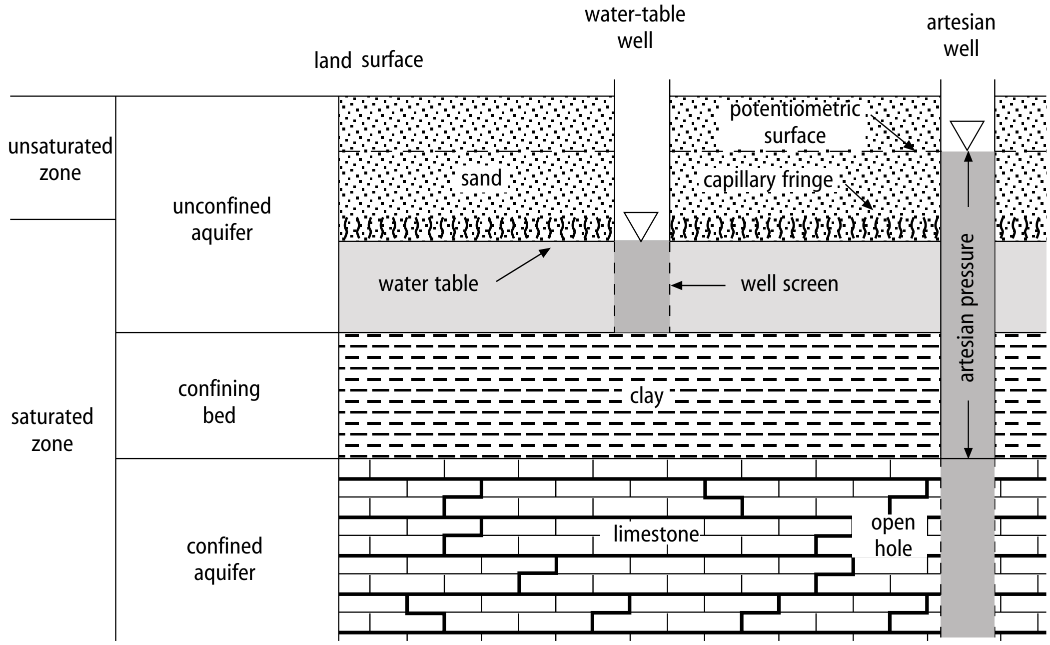

Figure 5: Types of aquifers
(Adapted from R.C. Heath, Basic Ground-Water Hydrology, *1989. Not to scale.)*

Movement of Groundwater

Like surface water, groundwater flows under the influence of gravity; but unlike rivers and streams, groundwater can move at an exceedingly slow rate, usually measured in feet or inches per day. In general, we can think of groundwater in a water table aquifer as essentially flowing from areas of high elevation to areas of low elevation. However, a more appropriate view is that groundwater flows from locations of high gravitational potential to locations of low gravitational potential. Depending on groundwater conditions, these gravitational potentials may or may not correspond to surface topography. Figure 6 shows an idealized flow pattern for groundwater in a uniformly permeable material. Groundwater always moves in the direction of decreasing gravitational potential.

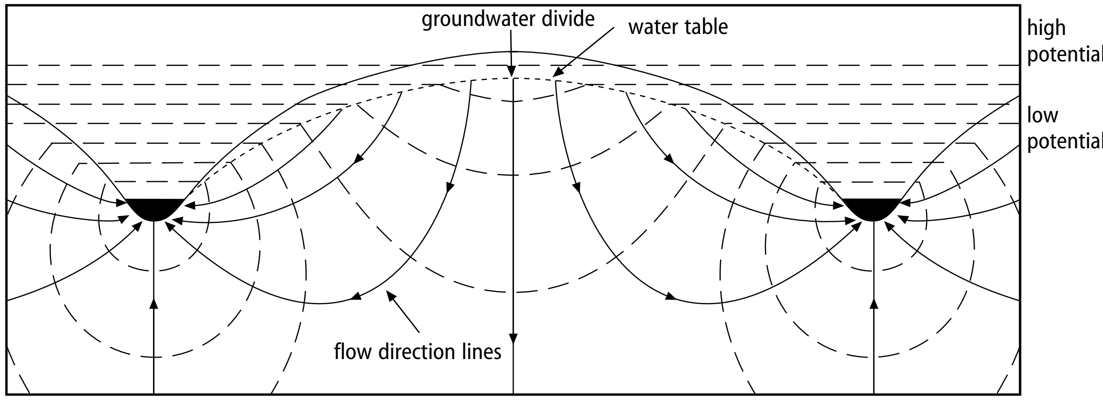

Figure 6: Flow of groundwater in a uniformly permeable material (Adapted from the EPA's Ground Water Volume 1, *1990.)*

The direction and degree of the slope of the water table (or the potentiometric surface in confined aquifers) is the driving "force" that causes groundwater to move. Most groundwater slopes are small, between 0.001 (1 foot drop in elevation per 1,000 feet in distance) and 0.01 (10 feet drop per 1,000 feet distance). For aquifers of a given hydraulic conductivity, the velocity of groundwater flow increases with increasing slope. Determining the direction and degree of the slope of the water table is very important in environmental investigations of contaminated groundwater because this determines how fast and in what direction contaminants will migrate.

Groundwater Wells

Groundwater can seep to the surface naturally at springs or into bodies of water. However, most groundwater is obtained from wells. A well is basically a hole in the ground filled with groundwater. The water in most drinking-water wells is usually extracted by a pump from a perforated pipe or casing placed in the hole. When a well is pumped, the water level in the well begins to lower as water is removed from storage in the well. The total head in the well becomes lower than the surrounding aquifer, causing water to flow from the aquifer into the well. This movement of water into the well results in lowering of the water level around the well. This cone of depression (see Figure 7) is an important factor to consider when withdrawing groundwater. For example, shallow wells can eventually go dry if pumping lowers the water table below the bottom of the well.

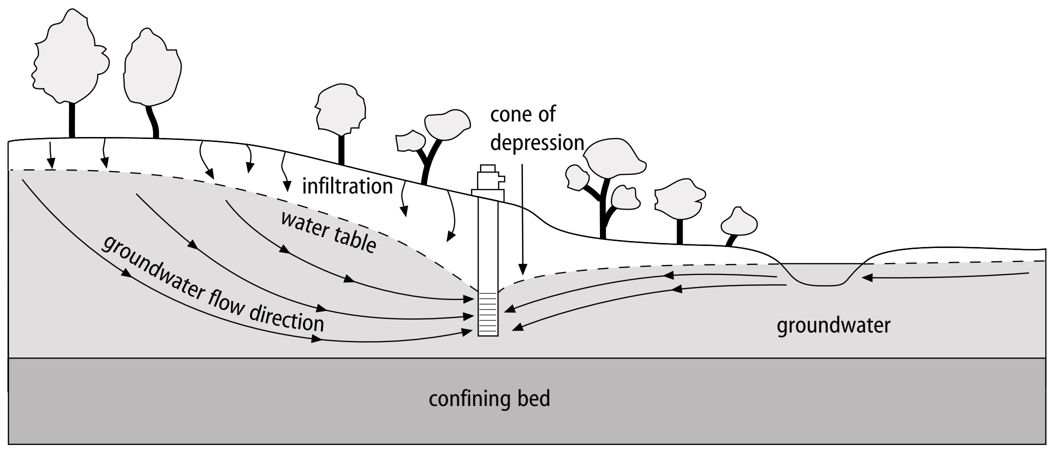

Figure 7: Cone of depression around a pumping well

Groundwater Quality

Not all groundwater is fit to drink (potable). Even though percolation through the ground effectively filters out most organic debris (such as leaves and organic compounds from leaves), groundwater can pick up minerals as it moves through subsurface rocks and soil. The types and amounts of dissolved minerals in groundwater depend on the biological and chemical reactions in the ground surface and soil zone and on the mineral composition of the aquifer. For example, water in limestone aquifers commonly contains a lot of calcium ions, resulting in hard water. Other common inorganic ions in groundwater include iron, magnesium, manganese, sulfate, sodium, and chloride. Concentrations of these ions are usually measured in parts per million (ppm). These constituents generally affect the taste or appearance of the water and are usually not considered harmful in low to moderate concentrations. For example, even a small concentration of dissolved iron can give the water a rusty appearance. Municipal groundwater treatment plants can reduce these impurities through filtration, aeration, reverse osmosis, and similar methods.

The farther, deeper, and longer that water migrates through an aquifer, the more dissolved minerals it picks up. Much of the deeper groundwater on Earth has more dissolved ions than seawater. However, in general, groundwater in an uncontaminated aquifer that is pumped from a properly installed well may be consumed with minimal treatment.

Groundwater Pollution

Pollution of groundwater by human activities has received considerable attention from private citizens and from Federal and state regulatory agencies over the last several decades. Protecting aquifers from pollution must continue to be a high priority as the nation's groundwater needs increase.

Pollution from septic tanks and from the application of fertilizers and pesticides is a serious problem affecting groundwater quality, particularly in rural areas. In areas without sewer systems or sewage treatment facilities, home owners commonly employ a septic tank and associated leach field designed to release waste slowly so that it can undergo natural degradation. When septic systems are improperly designed or placed, they can leak dangerous bacteria and viruses to groundwater. According to the EPA Handbook *Groundwater Volume 1,* effluent from septic tanks is probably the major cause of groundwater contamination in the United States.

In many parts of the country, groundwater becomes contaminated through intense agricultural use of pesticides. Also, nitrates, formed by nitrification of ammonia fertilizers, are a groundwater-pollution problem in many areas. According to one EPA document, more than 32,000 different compounds, including some highly toxic ones, are currently used in agricultural applications. Fortunately, many pesticide compounds are not highly mobile in groundwater because they tend to quickly adsorb to fine-grained particles, such as silt and clay. However, enough may get into the water supply to cause concern. One 1989 investigation sampled water from 188 wells in 10 agricultural counties in Texas. Nine pesticides were found in 10 of the wells. Nitrate levels were above recommended limits in 101 of the wells. Although nitrates are relatively nontoxic substances, certain bacteria can convert nitrates to nitrites. The consumption of nitrite-rich water can lead to a disease in infants known as "blue babies" (methemoglobinemia.)

Groundwater can also become contaminated from releases of industrial chemicals. Nearly all of the substances used in industry are soluble to some degree in groundwater and some can be toxic even in small concentrations. An estimated 20,000 abandoned or uncontrolled hazardous waste sites are thought to exist in the United States today. These sites can pose a threat to groundwater if they include drums, storage tanks, or other containers that have leaked their contents into the ground.

Regulatory agencies are particularly concerned with groundwater contamination from organic compounds created by the synthetic organic chemical industry, which has proliferated since World War II. Of the approximately 63,000 synthetic organic chemicals commonly used in industry and commerce, about 175 have been documented in groundwater.

The behavior of an organic substance in groundwater depends on its density and solubility in water. Most petroleum products, such as gasoline, are immiscible and less dense than water; they tend to spread out in a thin "free-phase" layer on top of the water table. Other substances, such as many chlorinated solvents, are more dense than water and tend to sink to the bottom of the aquifer. The behavior of these contaminants affects how much of a threat they pose to wells. Petroleum contaminants are largely confined to the vicinity of the water table, while chlorinated solvents can move downward and outward to contaminate deeper portions of regional aquifers from which many municipalities obtain their water supply.

Sources of groundwater contamination in urban and suburban settings include underground storage tanks (like the ones at a gas station), landfills, and road-salt storage areas. Landfills, both active and closed, are a particular concern because wastes are commonly placed very close to the water table. Rainwater infiltrating through a landfill dissolves contaminants, forming a leachate as the water migrates downward. Older, often abandoned, landfills have few engineering controls to prevent leachate from entering groundwater.

Once groundwater becomes contaminated it can be very difficult to clean up. Groundwater tends to have low biological activity, so biodegradation proceeds at a slow rate. One standard method for treating groundwater contaminated with volatile organic compounds (found in gasoline and many industrial solvents) is to pump the water out of the ground and run it through an air stripper, which causes the compounds to evaporate. The water is then returned to the ground. Another method of treatment is to inject air and nutrients into the aquifer to speed up microbial activity and thus the rate of biodegradation. These methods can be very expensive and require many years to complete.

Another groundwater quality issue that is a concern for people in coastal areas is saltwater encroachment. Near the ocean and on offshore islands, fresh groundwater often "floats" on the more dense salty groundwater below. If wells are pumping the fresh water at a high enough rate, the well water becomes brackish or salty from the flow of salt water into the cone of depression.

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