ABCs of Hydrogeology

Before learning how substances and land-use practices threaten groundwater, let's look at its origin, occurrence, and movement

BEFORE describing the threats to Virginia's underground waters, we want to introduce the water cycle and basic *hydrogeology* — the study of groundwater. Because it is hidden beneath the earth's surface, many people have trouble visualizing groundwater and understanding its origin, occurrence, and movement. The study of groundwater is a complex science, and we do not have the space to present a complete description of that science here. However, we hope this brief and general introduction to groundwater will help readers understand some of the factors influencing groundwater contamination. For readers who want more information, we have listed a number of texts and reference books in Appendix D.

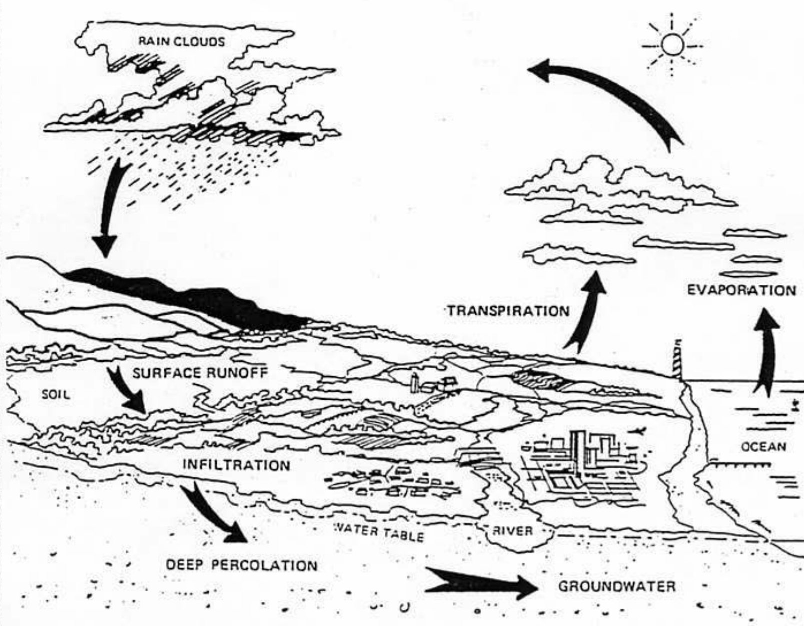
Hydrologic Cycle

THE constant movement of water above, on, and under the earth's surface is known as the *hydrologic cycle*. Water molecules move among "water compartments" of the cycle: fresh waters on the surface (lakes, rivers, and glaciers), living organisms, underground waters, the oceans, and atmospheric water. Although the movement through these components of the cycle is continuous, the span of time it takes to totally replace water in the atmosphere — nine days — is very different from the 37,000 years needed to totally renew the large volumes of water stored in the oceans. The hydrologic cycle has neither a beginning nor an end, but we'll select moisture-laden clouds in the atmosphere to begin our explanation.

Clouds release moisture, or *precipitation*, commonly as snow or rain. In Virginia, about 30.5 trillion gallons of water fall on the state's 40,817 square-mile area every year, according to estimates by the U.S. Geological Survey. The average annual precipitation ranges from 36-50 inches a year, with extreme southeastern and southwestern portions of the state receiving the most. Much atmospheric moisture evaporates before it reaches the earth, but that which falls to land can moisten the soil.

Once the surface of the soil is moist, water may begin to *infiltrate*, or penetrate, to deeper subsurface zones. The rate at which water moves laterally and downward through soil layers depends on soil type, land use, amount and duration of precipitation, and extent of vegetation. When the rate of precipitation exceeds the rate of infiltration, water flows over the surface of the land as *runoff*. Precipitation and surface runoff supply some of the water that feeds streams, lakes, rivers, and oceans.

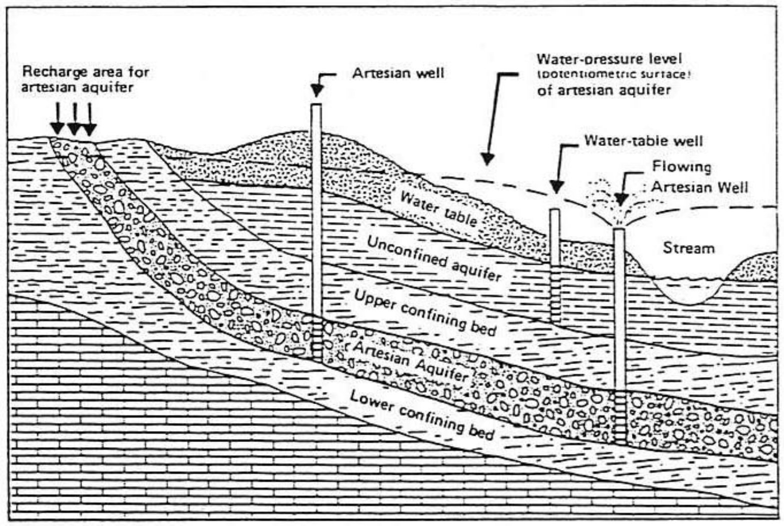
These surface bodies of water are also fed by water from underground. The water that seeps down through the soil's surface layer to the underlying soil and rocks is known as subsurface water, or underground water. This underground water reappears aboveground as springs and seeps and is an important source of supply to surface waters. Every year, about a billion gallons of groundwater discharge into the Atlantic and Pacific oceans, and according to the U.S. Geological Survey, 30 percent of the annual average flow of streams in Virginia is derived from groundwater.



A Cycle without Beginning or End . . .

Scientists call the constant movement of water from the atmosphere to earth to river to ocean the hydrologic cycle. How long it takes water that falls from the clouds to return to the atmosphere varies tremendously. After a short summer shower, it may be only a matter of minutes before most of the rainfall has evaporated into the atmosphere. A drop of rain falling on the ocean may take as long as 37,000 years before it returns to the atmosphere, and some water has been in the ground for millions of years.

Most moisture entering the soil is returned to the atmosphere through simple evaporation or through a more complex process known as *transpiration*. This latter process occurs when plant roots in the soil take up water, some of which eventually escapes into the atmosphere through the plant's leaves. The combined loss of water through evaporation and transpiration is known as *evapotranspiration*. The evapotranspiration of water — from the oceans and other surface waters, the land, and vegetation — and its return to the atmosphere where it reforms clouds completes the hydrologic cycle.



A Word about Aquifers and Artesian Wells

Aquifers can be confined or unconfined. A confined or artesian aquifer is one in which the water is under pressure. A flowing artesian well taps an aquifer where the water is under enough pressure to rise to the land surface without pumping. The recharge area for an unconfined or water-table aquifer may include all the land surface above it; for a confined aquifer, the recharge area is typically less extensive. For both types of aquifers, it is important to protect recharge areas from land-use activities that might contaminate the aquifer.

Basic Hydrogeology

MOST of the soil and rock formations within a half-mile of the earth's surface consist of solid rocks and minerals and the empty spaces between and within them. The empty spaces are called voids or pores. These voids can hold gases or fluids, including the underground water that supplies wells and springs. A deep vertical cut down through the earth's soil and underlying rock layers would show that underground water occurs in two zones. The uppermost zone — called the *unsaturated zone* or the *zone of aeration* or *percolation* — contains both air and water in the voids. Below this region occurs the *saturated zone*, where all interconnections, voids, and cracks are filled with water. Water in the saturated zone is properly called *groundwater*. Groundwater occurs in the voids between soil and rock particles much as water fills the pores of a sponge. The formation in which groundwater occurs is referred to as an *aquifer*.

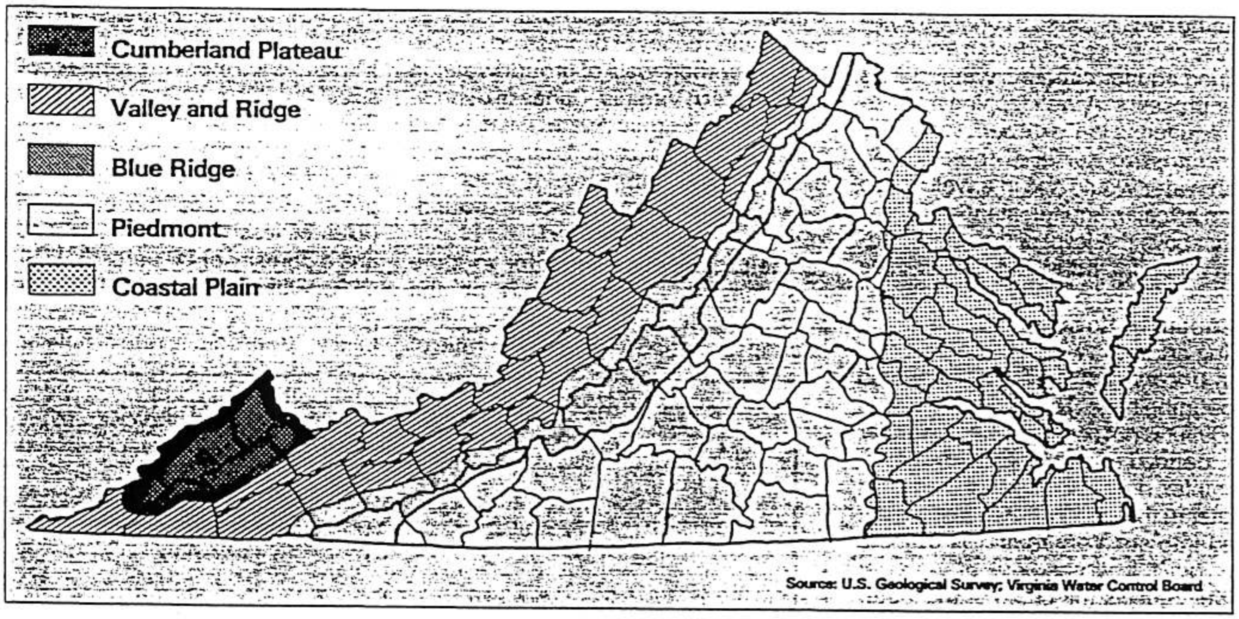
Water-bearing formations may be loosely associated or soil-like (*unconsolidated*) or a solid mass (*consolidated*). The surface of the earth is composed of soil and unconsolidated deposits that vary in thickness from less than an inch to several miles. For example, in areas of consolidated outcrops such as the Canadian Shield, a plateau which extends over half of Canada, the soil at the surface may be only a few millimeters (less than a tenth of an inch) deep — or lacking altogether. Below the Mississippi River delta, on the other hand, soil and unconsolidated deposits extend to more than 12,000 meters (7.4 miles) below the surface of the earth. The particles in unconsolidated deposits, ranging in size from clay (0.004 millimeters or less — less than a thousandth of an inch) to boulders (256 to 4,096 millimeters — 10 inches to 13 feet) are derived from the weathering of consolidated deposits and the reworking of unconsolidated deposits. Physical and chemical processes can weld unconsolidated materials together to form consolidated deposits — *limestone*, dolomite, shale, siltstone, and conglomerate are examples.

The flow of water through rocks depends on the consolidation process which formed them. Groundwater in *sedimentary* formations, or "grainy" rocks formed by sediments deposited in layers, flows between grains, much as it does in an unconsolidated deposit such as a layer of sand. Limestone and sandstone are both sedimentary rocks. *Crystalline rocks*, formed by great heat, pressure, or chemical reactions into solid masses, usually lack pore spaces. *Metamorphic rocks*, such as slate, and *igneous rocks*, such as granite, are both types of crystalline formations. In metamorphic rocks, water flow and storage can occur both between grains and within fractures. Groundwater flow and storage in igneous rocks is usually via fractures, faults, and cracks.

Pores formed at the same time the rock is formed, such as those found in sand, gravel, and lava, are called primary openings. Openings created after the rock is formed, such as cracks in granite or solution channels in limestone, are called secondary openings. Many sandstones and limestones and other sedimentary rocks have both primary and secondary openings, and groundwater may be stored in both types of openings.

Aquifers: Confined and Unconfined
Most formations beneath the unsaturated zone can be considered either an aquifer, a water-bearing consolidated or unconsolidated unit, or a *confining bed* or *aquitard*, a rock or soil unit th-' restricts the movement of groundwa into or out of adjacent aquifers. Aquifers can be confined or unconfined.

An aquifer completely filled with



Geologists Find Virginia Fascinating Place

To a geologist, Virginia is a fascinating place because of its geologic diversity. The Commonwealth has five distinct areas — called *physiographic provinces* — of similar geologic structure and climate. The geology of each province affects the quantity and quality of groundwater in it. The descriptions below are based on information from the Virginia Water Control Board.

Cumberland Plateau

The Cumberland Plateau is underlain by sandstone, shale, and coal. Groundwater is generally of poor quality, tending to be sulfurous and iron-rich. Naturally saline waters occur at depths greater than 300 feet. In coal mining areas, some groundwater has become acidic and is unsuitable for most uses. Wells generally yield from 10 to 50 gallons a minute. The potential for groundwater pollution is moderate in the Cumberland Plateau.

Valley and Ridge

Limestone, dolomite, shale, and sandstone are the common rock types in the Valley and Ridge province. Where limestone dominates, groundwater yields may be as high as 3,000 gallons a minute. Ridges and upland areas are often underlain by sandstone and shale, which yield only enough water for domestic use.

The relationship between groundwater and surface water is easily recognized here. In limestone areas, sizable surface streams disappear into underground channels and, conversely, some large springs emerge to become the headwaters for rivers.

Groundwater quality is affected by the chemical composition of rock formations. Limestone, for example, contributes to the "hardness" of water in this province.

The pollution potential in the Valley and Ridge is very high. Streams and surface runoff entering sinkholes contribute to the recharge of Valley and Ridge aquifers, providing direct conduits for contaminants.

Blue Ridge

The Blue Ridge province is a relatively narrow zone of mountains with the highest elevations in the state. The rocks underlying the area are granite, gneiss, and marble. Steep terrain and thin soil covering result in rapid surface runoff and low groundwater recharge. Groundwater use is primarily limited to domestic wells yielding less than 20 gallons a minute. Water quality is generally good, but the iron content is high in some locations. Groundwater pollution potential is low.

Piedmont

The Piedmont extends from the fall line — an imaginary line passing through Emporia, Petersburg, Richmond, Fredericksburg, and Fairfax — to the Blue Ridge Mountains.

The subsurface geology of the Piedmont province is diverse, resulting in wide variations in groundwater quality and well yields. In areas dominated by hard, crystalline rocks, most groundwater is found in faults and fractures within a few hundred feet of the surface. Well yields commonly range from 3 to 20 gallons a minute. Groundwater is generally of good quality; in a few areas, high iron concentrations and acidity cause problems. Recently, the crystalline rocks of the Piedmont have been examined as a potential site for disposal of radioactive wastes and hazardous chemicals.

Pollution potential is rated as moderate to low.

Coastal Plain

Extending from the fall line to the coast, the Coastal Plain is composed primarily of sand, gravel, clay, shell rock, and other unconsolidated deposits. This province stores more groundwater than any other in the state. About half the state's groundwater use occurs in the Coastal Plain. In many areas, the shallow water-table aquifer provides water for hundreds of domestic wells with yields of 10 to 50 gallons a minute. The deeper system of artesian aquifers is the primary source of water for municipal and industrial use. Some large production wells yield 2,000 to 3,000 gallons a minute. Water quality is good, except in a few areas where salt water, iron, and hydrogen sulfide occur.

The highly permeable soils in the Coastal Plain and the high population density result in a high pollution potential, especially for the shallow aquifers.

water and surrounded on all sides by confining beds is called a *confined aquifer*. Also known as an *artesian aquifer*, a confined aquifer contains water that is under pressure. A well tapping an artesian aquifer is an *artesian well*. The *potentiometric surface*, the level to which water would rise in a well drilled into an artesian aquifer, stands at some height above the level of the upper confining bed. If the potentiometric surface is above the land surface, then the well continuously flows and is called a flowing artesian well.

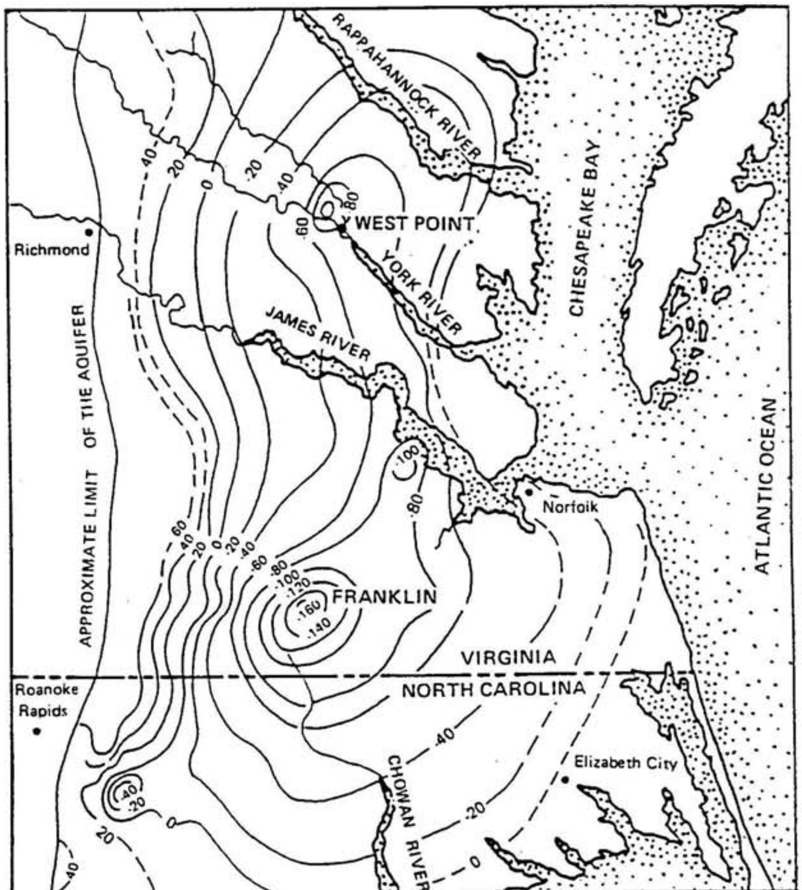
An *unconfined aquifer* is not bound by confining beds. The upper surface of the aquifer is not confined, and the *water table*, defined as the height of water in the aquifer, rises and falls as the amount of water in the aquifer fluctuates. A well drilled into such an aquifer is called a *water table well*; the level of water in the well reflects the depth of the water table in the surrounding aquifer. In some areas, relatively small volumes of water may occur above the water table. This water, collected on top of an unsaturated soil or rock layer above the main body of groundwater, is called *perched water*. The water table is not usually level; more often it reflects the surface topography above it and has "hills" and "valleys" just as the land surface does. In general, the water table is at depths of zero to twenty feet in humid areas and can be hundreds of feet underground in desert areas.

The depth of the water table beneath the land surface influences land use and development of water supplies. Where the water table is close to the surface, land is marshy or "waterlogged" during wet weather and unsuitable for residential and other uses. Alternately, the cost of constructing wells and pumping water may be prohibitively expensive where the water table is far beneath the surface.

Cones of Depression Wells tapping both confined and unconfined aquifers can cause the formation of *cones of depression*, or "valleys," in the aquifer. This decline in water level in the vicinity of a well may extend for just a few feet or hundreds of feet around a well in an unconfined aquifer, but in a confined aquifer a cone of depression may be miles in diameter. Wells that are close together may have overlapping cones of depression. Because the "drawdown" effect is additive, water level decline in an aquifer is greater where overlapping cones of depression occur than where there is a single cone. The map below shows the extensive area affected by overlapping cones of depression caused by large withdrawals of groundwater in southeastern Virginia. Cones of depression influence groundwater velocity and direction of flow, and their existence must be taken into account when the movement of contaminents in groundwater is being investigated.

The capacity of an aquifer to store and transmit water depends on the *porosity* of the rock or soil in the water-bearing formation. Porosity, the ratio of voids or pores to the total volume of soil or rock, indicates the maximum amount of water a formation can contain when it is saturated. Both the range of particle sizes and their shape affect porosity. Clay, composed of tiny particles ar voids of uniform shape and size, has porosity of about 50 percent, whereas gravel, which is composed of rock particles of less uniform shape and size, has a porosity of 20 percent.

For water in an aquifer to be useful to people, it must be pumpable to the surface at a reasonable rate of flow and at a



Source: U.S. Geological Survey

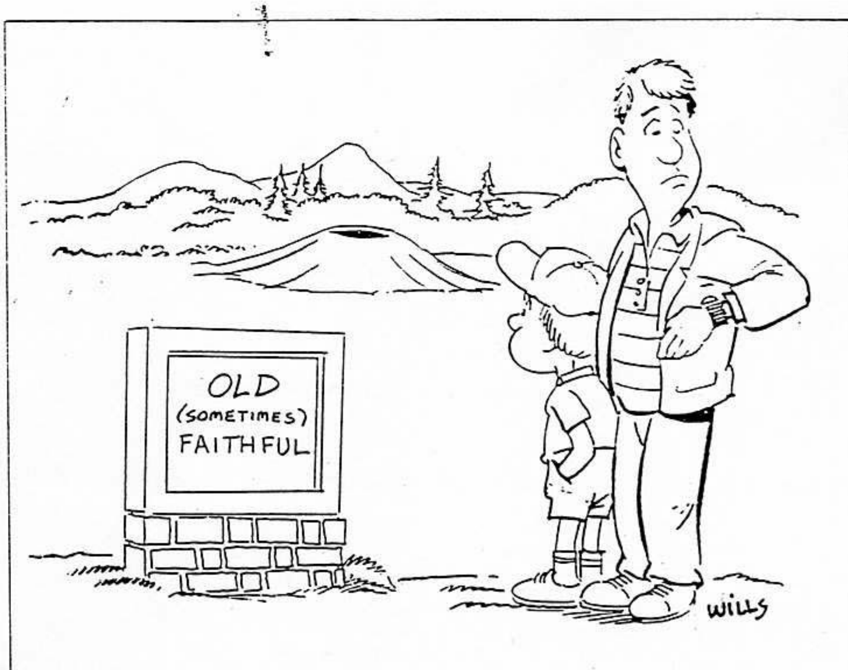
That Sinking Feeling in the Coastal Plain

Withdrawals of about 73 million gallons a day from well fields have caused two giant cones of depression to form in an extensive confined aquifer in Virginia and North Carolina. Pumping by papermaking industries in Franklin and West Point, Virginia, is responsible for more than 60 percent of the daily withdrawal. In this area, such cones of depression can result in saltwater intrusion or the collapse of the water-bearing formation and land above it. The numbers on the map represent height in feet of the aquifer's potentiometric surface relative to mean sea level. Around Franklin, the depth to groundwater below the land surface had declined 165 feet since the 1930s but has recently stabilized.

reasonable cost. Although an aquifer may have a high storage capacity, or porosity, its water may not be easily available. The term *specific yield* refers to the amount of water available from an aquifer for use by people. *Specific retention* refers to the amount of water unavailable for use because it is tightly bound to the rock unit by physical forces. Measurements of specific yield and specific retention for a particular aquifer equal its total storage capacity. For example, clay's porosity of 50 percent indicates that it has a high storage capacity. However, the water it holds is mostly unavailable; clay yields little water (specific yield of 2 percent) because physical forces bind the water to the clay particles (specific retention of 48 percent).

Materials with high specific retention have low *hydraulic conductivity* and are commonly termed *impermeable*. Materials have a low hydraulic conductivity or a low ability to transmit water because the pores and voids in the material are not interconnected. Interconnections of openings in limestone and granite allow these rock units to yield much of their available water.

An ideal aquifer for a water supply would have a high storage capacity, high specific yield, high hydraulic conductivity, and good water quality. Unconsolidated sand and gravel aquifers generally are highly productive because they have both high permeability and porosity. In fact, sand and gravel aquifers are the main source of water for most wells in the United States. Unfortunately, their high permeability (high hydraulic conductivity) also makes them more vulnerable to contamination.



No Longer Faithful

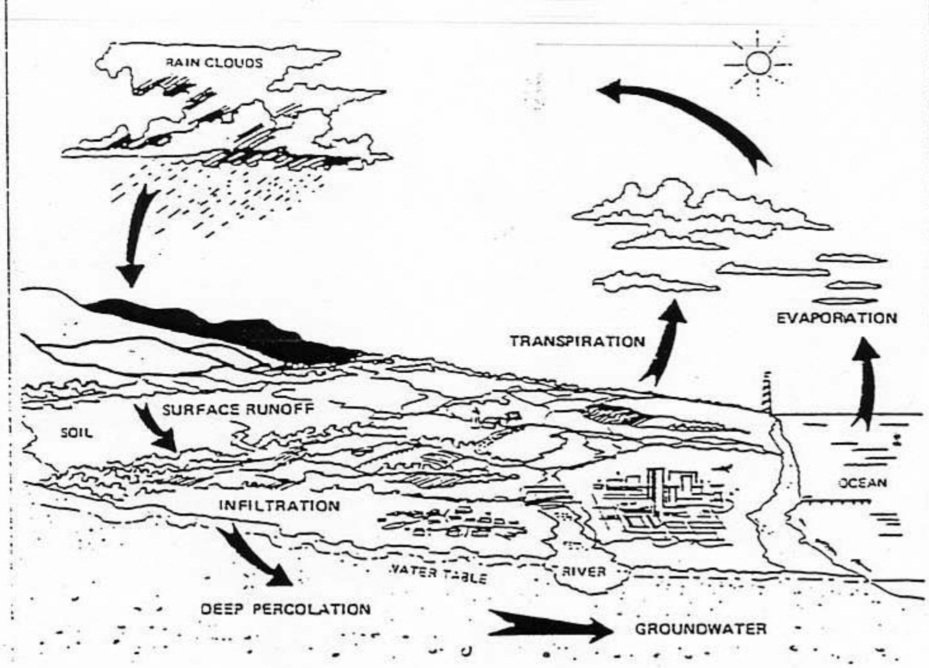
Old Faithful, the Yellowstone National Park geyser so named because of its dependability, can no longer be trusted to erupt on schedule. An earthquake in Idaho disrupted its groundwater system. Eruptions which used to occur 65 minutes apart now average 78, with as long as 90 minutes between bursts.

Recharge and Discharge Aquifers can be thought of as porous conduits filled with sand and other materials that transmit water from *recharge* to *discharge* areas. Any addition to the groundwater supply is recharge and any removal from this supply — whether it be to pumping wells, springs, seeps, streams, or marshes — is discharge. In the eastern United States, precipitation exceeds evapotranspiration, and annual average recharge of aquifers generally equals or exceeds discharge. In the arid southwestern United States, annual precipitation is less than 10 inches; rates of evapotranspiration are potentially 4 to 20 times greater than precipitation, and recharge may not balance discharge for years or even centuries.

The values for annual precipitation and recharge in Virginia can be used to estimate the impact of human use on the state's groundwater. Assuming about 10 percent — a conservative value — of Virginia's total annual precipitation (30.5 trillion gallons) is available as recharge to groundwater, this would equal an annual statewide recharge of 3 trillion gallons. In 1980, total annual groundwater use was about 142 billion gallons (389 million gallons per day for 365 days), according to the Virginia Water Control Board and the U.S. Geological Survey. Based on these estimates, the total groundwater supplied to all users — domestic, agricultural, industrial, and thermoelectric — was only 4.5 percent of the annual average recharge. However, large withdrawals of groundwater in specific locations in Virginia have caused the water table to drop locally, forming extensive cones of depression around the withdrawal points. The use of groundwater which results in discharge exceeding recharge is referred to as overpumping or mining.

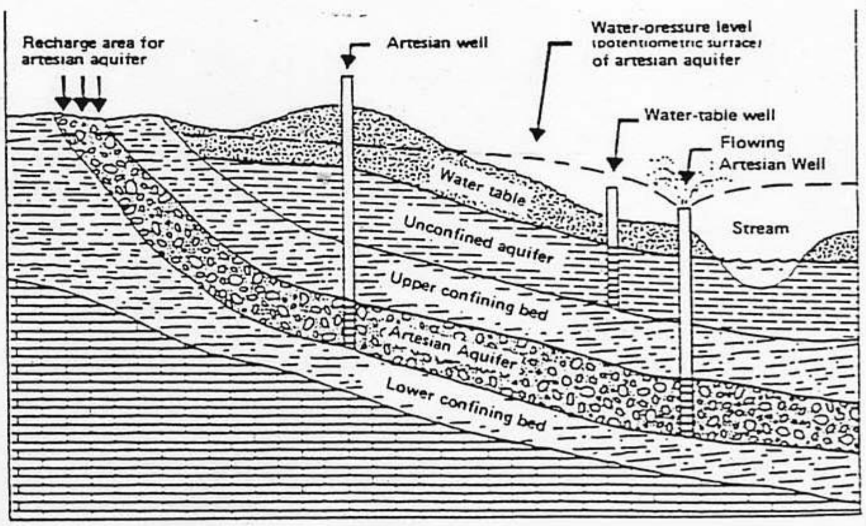
Many people greatly overestimate the rate of groundwater's movement from regions of recharge to discharge because they mistakenly think groundwater flows at rates similar to those of streams and rivers. The average rate of water movement through an aquifer composed of coarse sand is 0.3 meters per day (360 feet per year), whereas the average rate through a clay confining bed is 0.00002 meters per day (less than half an inch per year). Only in limestone caverns, open lava tubes, or large rock fractures can the rates of groundwater movement resemble those of streams and rivers on the surface. The movement of contaminants through such formations is likewise very rapid.

Because the movement of water from recharge to discharge areas is generally so slow, groundwater at any one place may be very old. According to the U.S. Geological Survey, groundwater within 800 meters (half a mile) of the land surface has been underground for an average of 200 years. For aquifers deeper than 800 meters, that average is 10,000 years. This slow movement means groundwater contamination can have long-term effects. Toxic chemicals spilled into surface streams often are quickly "flushed" from the area and diluted by the large volumes of water moving rapidly over the streambed. The same chemicals spilled into an aquifer could remain for hundreds or thousands of years.



A Cycle without Beginning or End . . .

Scientists call the constant movement of water from the atmosphere to earth to river to ocean the hydrologic cycle. How long it takes water that falls from the clouds to return to the atmosphere varies tremendously. After a short summer shower, it may be only a matter of minutes before most of the rainfall has evaporated into the atmosphere. A drop of rain falling on the ocean may take as long as 37,000 years before it returns to the atmosphere, and some water has been in the ground for millions of years.



A Word about Aquifers and Artesian Wells

Aquifers can be confined or unconfined. A confined or artesian aquifer is one in which the water is under pressure. A flowing artesian well taps an aquifer where the water is under enough pressure to rise to the land surface without pumping. The recharge area for an unconfined or water-table aquifer may include all the land surface above it; for a confined aquifer, the recharge area is typically less extensive. For both types of aquifers, it is important to protect recharge areas from land-use activities that might contaminate the aquifer.