Groundwater & Wetlands

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Summary

We'll never know the worth of water till the well goes dry.

Scottish Proverb

I wish to make it clear to you, there is not sufficient water to irrigate all the lands which could be irrigated, and only a small portion can be irrigated . . . I tell you gentlemen, you are piling up a heritage of conflict!

John Wesley Powell

I derive more of my subsistence from the swamps which surround my native town than from the cultivated gardens in the village . . . I enter a swamp as a sacred place, a sanctum sanctorum. There is the strength, the marrow, of Nature.

Henry David Thoreau
Introduction

- Groundwater is water in rocks below Earth's surface.
- Most cave systems are formed by groundwater.
- A major court case in Woburn, Massachusetts, revolved around the rate of flow of solvents through a groundwater system.
- Most groundwater used in the U.S. is pumped for irrigation.

What do the world's largest cave, resurgent movie actor John Travolta, and agricultural economics have in common? In a word, **groundwater**.

Groundwater, water in rocks or sediment below Earth's surface, is just one element in the hydrologic cycle. The cycle, discussed in the first section of this chapter (Hydrologic Cycle), ties together the processes that cause water to change state (vapor, liquid, solid) as it moves between different elements of the earth system.

A recent movie, *A Civil Action*, highlighted the real story of a legal battle essentially decided by the geology of a groundwater system. The lawsuit was filed on behalf of a group of families from **Woburn, Massachusetts**. Children of the families were diagnosed with leukemia after their mothers drank water from two polluted wells (wells H and G, Fig. 1) while they were pregnant. The families' attorney, Jan Schlichtmann (played by John Travolta in the movie), tried to show that the wells were contaminated by industrial solvents (trichloroethylene [TCE] and tetrachloroethylene [PCE]) dumped illegally by nearby companies.

Figure 1. Relative locations of wells H and G and potential sources of pollution at Woburn, MA. Leukemia cases were clustered in the Pine Street neighborhood south of the wells. Properties near the wells included: W.R. Grace, NEP (Plastics), Olympia (trucking), UniFirst (dry cleaning), Wildwood (tannery).
The case revolved around how quickly specific solvents could travel through the groundwater system to reach the wells. Lawyers representing the plaintiffs and defendants called geologists as expert witnesses to determine how factors such as distance from wells, properties of the chemicals, and variations in local geology could be used to establish a time line for the contamination. The geologic interpretations were complicated by lateral variations in sediment character, the presence of fractures in the bedrock, the linkage between groundwater flow and a nearby river, and the role of wetlands and peat deposits in influencing groundwater flow. We will discuss how the natural properties of rock and sediment influence the distribution and flow of groundwater in the second section of this chapter (Rock Properties).

After more than two months of often complex scientific testimony, the jury found that chemicals from one company, W. R. Grace, could have contaminated the wells. Soon thereafter, Grace settled with the families for $8 million. The EPA later declared the area a Superfund site and several of the surrounding landowners agreed to pay nearly $70 million to clean up the 330-acre site (Fig. 2).

We will examine how water enters and leaves groundwater systems in particular we will review the characteristics of aquifers, underground water storage reservoirs. Approximately two-thirds of all the fresh groundwater pumped in the U.S. is used for irrigation of crops (Fig. 3). Precipitation drops to less than 50 cm (20 inches) per year over much of the western U.S. The paradox is that this semi-arid region is the source of a large proportion of our grain crops. Kansas, the wheat state, is too dry to produce wheat unless water is added by irrigation. The majority of the irrigation waters for the Great Plains states are taken from a single massive groundwater system, the High Plains aquifer.
**Human modifications of groundwater systems**, the last section on groundwater, examines how human interaction with the environment has resulted in a variety of groundwater problems, including depleted water supplies, pollution, and land subsidence.

**Introduction to wetlands** describes the conditions necessary for the formation of wetlands. Wetlands (Fig. 4) provide geologic (e.g., moderate flooding, recharge groundwater) and cultural (e.g., recreation), and economic (e.g., breeding grounds for commercial shellfish populations) benefits. Finally, we will discuss why these ecosystems are in decline with reference to the Florida Everglades, the nation's only subtropical ecosystem (*Destruction of Wetlands*).

![Figure 3. Uses of fresh groundwater in U.S., 1990. Nearly two-thirds of the 79 billion gallons of groundwater used per day were used for irrigation. Most of this was used in western states with relatively dry climates. Image courtesy of USGS water science for schools website.](image1)

**Think about it . . .**
Examine map data and complete the table at the end of the chapter to identify which parts of the U.S. have the greatest risk of future water shortages and which regions have a relatively abundant water supply.

![Figure 4. Northeast Ohio wetland developed in an oxbow lake formed by an abandoned stream meander.](image2)
Hydrologic Cycle

- The hydrologic cycle involves evaporation, condensation, runoff, infiltration, percolation, and transpiration.
- The bulk of Earth’s water remains in the oceans for thousands of years before participating in the hydrologic cycle.
- Most precipitation on land returns to the atmosphere by evaporation and transpiration.
- Groundwater represents two-thirds of all water on land.

The distribution of water on Earth is dependent upon the interaction between the land and the other three elements of the Earth system, the atmosphere, oceans, and biosphere. The circular path of the hydrologic cycle links evaporation, condensation, runoff, infiltration, percolation, and transpiration (Fig. 5). These processes cause water to change state (vapor, liquid, solid) as it moves between different elements of the Earth system.

The oceans are the ultimate source for all water on or below the land surface (Fig. 6). The average residence time - the length of time water remains in a given location - for oceanic water is 3,000 to 4,000 years. The bulk of evaporation (85%) occurs over oceans (Fig. 7) and is greatest in areas of warm climates at low latitudes. Water vapor cools and relative humidity of the air increases as it rises in the atmosphere. Condensation (water vapor converted to liquid) forms tiny moisture droplets that may coalesce to form clouds when the air becomes saturated with water vapor (100% humidity). Atmospheric circulation patterns may redistribute the saturated air prior to precipitation.

Precipitation is concentrated over areas of rising air and is least in areas of descending air. (See section on Global
Precipitation and Temperature in chapter, Earth's Climate System for more on the distribution of precipitation.) The volume of moisture in the atmosphere is equivalent to ~25 mm (1 inch) of precipitation. It is estimated that moisture in the atmosphere is recharged 40 times a year (residence time ~9 days) because the average annual precipitation for the world is approximately 1,000 mm. Nearly a third of all water falling as precipitation completes the circuit to the oceans by surface runoff in streams (average residence time 14 days). Most of the rest returns to the atmosphere by evaporation or through the transpiration of plants.

A slim fraction of water falling as precipitation infiltrates below the surface through bedrock or soils to form groundwater (Fig. 5). More water is present on Earth as moisture in rocks and soils than all the water in streams, rivers, and wetlands combined. Some of the soil moisture is lost to evaporation or taken up by vegetation and the remainder recharges the groundwater system. Groundwater flow is termed percolation and occurs at rates from meters per day to millimeters per year. Consequently the residence time for groundwater may be measured in intervals of weeks or

Figure 6. Water balance on Earth. The vast majority of Earth's water is in the oceans.

Figure 7. Land areas receive more moisture by precipitation than they supply by evaporation. The difference is made up by evaporation from oceans. This excess water is returned to oceans by surface runoff (streams).

Figure 8. Approximately 3% of the world's water exists on land, mainly in the form of groundwater or ice. Most (~90%) of groundwater contains concentrated salts and is too saline for human use.
thousands of years. Even the slowest flow rates will eventually return the groundwater to the ocean, completing the hydrologic cycle.

**Think about it . . .**
Predict what would happen to sea level if rain fell continuously all over the world. Explain your choice.

a) Sea level would rise.
b) Sea level would fall.
c) Sea level would stay the same.

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**Rock Properties**

- The distribution of groundwater is controlled by the porosity and permeability of rocks.
- Porosity is the capacity of rock or sediment to store water.
- Permeability is the capacity of water to flow through rock or sediment.
- Loose sand has a porosity of 30 to 40%.

There is approximately 40 times more water below ground than in lakes and streams on Earth's surface. **Cave systems** represent some of the most dramatic landforms generated by groundwater (Fig. 9). Although caves can be formed by other geologic processes, the **dissolution of limestone** by groundwater is the most common method of cave formation. (See the section on Chemical Weathering in the chapter, Weathering and Soils for more on how limestone is dissolved.) The world's largest cave, Mammoth Cave, Kentucky, is also one of the prime attractions of the U.S. national park system.

The flow of water through caves also generates one of the most commonly held misconceptions about groundwater. Groundwater is not made up of a network of underground rivers and lakes. Rather, most groundwater is present in billions of tiny spaces between mineral grains or in narrow fractures in bedrock. It helps to keep in mind that caves are relatively rare but groundwater resources are present nearly
Groundwater distribution depends on the **porosity** and **permeability** of rocks or sediment.

**Porosity**

Porosity is the capacity of rock or sediment to store water. Porosity may be over 50% of rock/sediment volume. Rock and sediment contain spaces between grains (**pore spaces**), in fractures, or in dissolved cavities (limestone), that may become filled with water.

The proportion of the rock made up of pore spaces is dependent upon the size and packing (arrangement) of the constituent grains (Fig. 10). Porosity is typically higher in unconsolidated sediments (sand, gravel) than in the equivalent rocks (sandstone, conglomerate) which have undergone lithification. The conversion of sediment to sedimentary rock...
results in the loss of porosity as a result of **compaction** (spaces destroyed as grains are squeezed closer together) and **cementation** (spaces filled with cementing agent holding grains together). Porosity may later be enhanced by dissolution in limestones (rock is dissolved by weakly acidic groundwater) or fracturing of all rock types during tectonic events.

Some groundwater is held as a film on the surfaces of grains by surface tension. This water will not flow through the rock and is termed the **specific retention** \( (S_r) \) of the material. The volume of groundwater that can drain from rock or sediment is known as the **specific yield** \( (S_y) \). Specific yield is calculated by subtracting specific retention from porosity.

The specific yield of coarse-grained rocks is little different from porosity because the surface film is a small proportion of the pore space. In contrast, surface films represent most of the water in the small pores between clay and silt particles in fine-grained rocks. Consequently, the specific yield of these materials is low even though porosity is high (~50%) in clay-rich sediments and rocks.

Igneous and metamorphic rocks typically have low porosity and permeability as their grains grow together during rock formation. However, the presence of fractures in some rocks produces properties suitable for the storage and flow of groundwater. Thousands of meters of ancient lava flows are preserved as the **Columbia Plateau basalts** in the northwestern U.S. The tops of the lava flows were heavily fractured during formation and the bases of the adjacent flows often contain abundant vesicles (gas bubbles). Wells penetrating these zones of high porosity and permeability can yield as much as 450 liters (117 gallons) of water per second.

**Porosity Demonstration**

A 1,000 ml beaker was filled with sand and 500 ml of water were added to a second beaker (Fig. 11). Water was slowly poured into the sand-filled beaker. The water moved down
through the sand (permeability), darkening the grains. We continued to pour the water until all the sand was completely saturated and water rose to the surface of the sand.

The water level in the second beaker had declined from 500 ml to 150 ml. The difference was in the sand-filled beaker. The 350 ml of water filled the pore spaces between sand grains. Therefore, 350 ml of the original 1,000 ml sand volume was made up of air-filled pore spaces (porosity = 35%).

Permeability

Permeability is the capacity of water to flow through rock or sediment (Fig. 12). Water can flow readily through rocks with high permeability values.

High permeability often goes hand-in-hand with high porosity and large grain size (Fig. 13). Connections between pore spaces are wider in coarse-grained sediment (sand, gravel) and rock (sandstone, conglomerate) and are narrower in fine-grained materials (silt, clay, shale, mudstone). However, not all pore spaces may be connected and others may contain clay minerals that can expand in the presence of water to block passageways and reduce permeability. Surface water films in fine-grained materials may fill the narrow connections between pore spaces blocking the passage of groundwater.

Numerous measurements of natural groundwater systems have revealed that groundwater flows much more slowly than water in streams because of the effect of friction from the surrounding grains. Rapid groundwater flow is measured in meters per year. In contrast, streams typically travel a meter in

Figure 12. Three stages of flow of groundwater between connected pore spaces. Permeability is greater (flow is faster) through the wider passage on the right. Note that not all pore spaces are interconnected.

Figure 13. Variation in permeability between different sediment types.
a few seconds. One benefit of the excruciatingly slow movement of groundwater is that pollution may be anticipated and mitigated before it contaminates underground water supplies. The net direction of groundwater flow is downward under the influence of gravity. An exception to the generally slow nature of groundwater flow is water flowing through well defined fracture systems or caves where flow rates can approach those of surface streams.

**Think about it . . .**

1. Predict how the porosity of gravel compares to the porosity of sand. Assume sand and gravel particles have the same shape and differ only in size. Explain your choice.
   a) Sand has higher porosity.
   b) Gravel has higher porosity.
   c) Porosity is the same for sand and gravel.

2. Predict how the permeability of gravel compares to the permeability of sand. Explain your choice.
   a) Sand has higher permeability.
   b) Gravel has higher permeability.
   c) Permeability is the same for sand and gravel.

3. Over two billion gallons of liquid waste was dumped at Otis Air Base, MA. Examine the diagram below and predict which time interval is the best estimate as to how long it would take for the waste to appear in drinking water wells in Falmouth?
   a) 6 months  b) 6 years  c) 60 years  d) 600 years

![Diagram](image)

**Groundwater Systems**

- Aquifers are rocks or sediment that act as storage reservoirs for groundwater.
- An aquitard is rock or sediment that represents a barrier to groundwater flow.
- Water infiltrates into open aquifers from above.
• Open aquifers contain a saturated zone where pore spaces are filled with water.
• The water table is the top of the saturated zone.
• Water enters closed (artesian) aquifers from a recharge area.

Aquifers are rock or sediment that act as storage reservoirs for groundwater and are typically characterized by high porosity and permeability. In contrast, an aquitard (or aquiclude) is composed of a low-permeability rock or sediment that essentially acts as a barrier to groundwater flow. Water has been found in wells that have penetrated as deep as 9 km (over 5 miles) into Earth's crust. Most usable fresh groundwater is relatively shallow (less than 100 meters [330 feet]). Deeper waters are more expensive to retrieve and often contain high concentrations of minerals. Aquifers (and aquitards) are typically in sediments or sedimentary rocks as these rock types are found at Earth's surface more frequently than relatively impermeable igneous and metamorphic rocks.

Open Aquifers

Aquifers can be divided into open (unconfined) aquifers and closed (artesian or confined) aquifers. In an open aquifer, water infiltrates through permeable soil and rock or sediment that make up the unsaturated zone in which pore spaces are only partially filled with water. Water passes downward into the saturated zone of the aquifer where all the pore spaces are filled with water (Fig. 14). The top of the saturated zone (base of unsaturated zone) is the water table.
The water table mimics the shape of the land surface as it is higher under hills and lower in valleys. The elevation of the water table will fluctuate with variations in precipitation. The water table will drop during prolonged dry periods and rise again when precipitation is plentiful. Wells must be drilled far enough into the saturated zone to ensure a year-round supply of water. Groundwater will flow down the hydraulic gradient from areas where the water table is high to areas where it is low, however, the flow paths may vary from straight lines to long looping curves (Fig. 15). The orientation of the flow path is controlled by geologic conditions (e.g., rock type, fractures).

Closed (Artesian) Aquifers

A closed (artesian) aquifer is confined by an overlying aquitard that prevents water from simply infiltrating down into the aquifer. Instead, water enters the tilted aquifer layer through a recharge area where the aquifer rock is exposed at higher elevations. Flow in an artesian aquifer resembles water flowing through a J-shaped tube (Fig. 16). Pressure from the overlying water column in the aquifer (Fig. 17) is sufficient to cause groundwater to rise above the level of the aquifer. Water in artesian wells will rise above the aquifer itself and may reach the surface (Fig. 17).

Settlers on the plains of South Dakota in the early 1900s observed water gushing to 100 feet above the ground surface in artesian wells drilled into the Dakota sandstone. The aquifer was recharged by rainfall in the Black Hills to the west. There were over 10,000 wells drilled into the aquifer by 1915. Inevitably, the water table fell requiring many of the wells to add pumps to bring water to the surface.
Natural Groundwater Budget: Recharge vs. Outflow

The origin of groundwater is dependent on two current natural sources (infiltration, streams) and on the recent geologic history of the aquifer system (storage).

- **Infiltration**: Rainfall infiltrates through soil, sediment, and permeable bedrock to replenish open aquifers or through recharge areas for closed aquifers. There are relatively small seasonal variations in the elevation of the water table and greater changes during prolonged droughts or periods of sustained precipitation. The volume of precipitation that enters an aquifer is dependent on the temporal and spatial distribution of precipitation and the character of the ground cover. Steady, regional rainfall will replenish an aquifer more than torrential local storms. Likewise, rain falling on farm fields or natural lands is more likely to infiltrate below ground than rain falling in urban areas where it will descend into storm sewers en route to a nearby stream.

- **Streams**: The water table is often far below the ground surface in areas with dry climates. Permanent streams flowing through these areas may lose water to groundwater through the stream banks and bed. Such streams are termed losing (effluent) streams (Fig. 14). Unlined canals and surface reservoirs, built to supply irrigation waters from the Colorado River, act like losing streams in the desert Southwest.

- **Storage**: The climate of North America is warmer and drier today than it was prior to the close of the last great Ice Age (10,000 years ago). Much of the water in many U.S. aquifers represents this ancient groundwater source. Much of this water will not be replenished by streams or precipitation but instead represents a finite resource that cannot be replaced once used.
Water will eventually leave the groundwater system at one of three discharge points defined by streams, springs or wetlands, and the ocean:

- **Streams**: Groundwater may flow into streams in areas with relatively high water tables. These streams are termed **gaining streams** (Figs. 14, 18). Depending on the region, groundwater can account for most of the base flow of a stream. For example, the Sturgeon River, Michigan, flows over permeable sands and gravels and receives approximately 90% of its minimum discharge from groundwater (Fig. 18).

- **Wetland/spring**: Water may flow out at the ground surface from a spring or wetland located where the water table intersects the ground surface (Fig. 14). Springs may form where fracture systems or cave systems (Fig. 19) reach the ground surface. An **oasis** represents an equivalent feature in a desert (Fig. 19).
• **Ocean discharge:** Groundwater will discharge to the ocean along the coast. A lens of fresh groundwater floats above more dense salt water in coastal regions (Fig. 20). Coastal cities extract water from the freshwater lens. Over-pumping may cause salt water to enter water wells (**salt water intrusion**) and pollute the water supply (Fig. 20). Salt water intrusion has been a problem for communities in Long Island, New York, and along the southeast coast of Florida.

![Figure 20. Salt water intrusion occurs when coastal wells pump too much water and draw up salt water that is normally isolated below the freshwater lens.](image)

**Think about it . . .**

Answer the two concepttest questions on groundwater systems found at the end of the chapter.

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**High Plains Aquifer**

• Agriculture from South Dakota to Texas has been supported by irrigation from the High Plains aquifer for nearly a century.
• The aquifer is an open system mainly developed in shallow sands and gravels.
• Much of the water originally entered the aquifer during a wetter climate during the last Ice Age.
• Groundwater overdraft occurs when water is extracted from the aquifer more rapidly than it can be recharged.

Precipitation drops to less than 50 cm per year (20 inches) over much of the western U.S. The paradox is that this **semi-arid** region is the source of much of our produce and grain crops.
Kansas, the wheat state, is too dry to produce wheat unless water is added by irrigation. Irrigation waters for many of the Great Plains states (North Dakota south to Texas) are taken from a single massive aquifer, the High Plains aquifer (Fig. 21).

The High Plains aquifer extends from southernmost South Dakota to the panhandle of Texas. The aquifer has been a source for irrigation water since the arrival of the region's earliest settlers over a century ago. Early explorers dubbed the region "The Great American Desert." Leading an expedition through the area in 1819, Major Stephen Long considered it as "almost wholly unfit for cultivation and . . . uninhabited by people depending upon agriculture for their subsistence." Today there are 170,000 wells that draw water from the aquifer throughout an area of 480,000 square kilometers, making it the largest area of irrigation-sustained cropland in the world (Figs. 21, 22).

The sand and gravel aquifer is unconfined (open) and is recharged by water infiltrating from above. Limited recharge occurs from precipitation (Fig. 22) and stream outflow. The aquifer's saturated zone is up to 425 m thick but aquifer dimensions vary along its length. It is always relatively shallow; the water table is typically less than 100 meters deep. The aquifer contains more than 3.3 billion acre-feet of water (1 acre-foot = ~326,000 gallons), more than the volume of water in Lake Huron.

Unfortunately for agricultural interests in the Great Plains, there is no contemporary source for water to recharge the whole aquifer. Most of the water in the aquifer entered the
groundwater system over 10,000 years ago during a wetter climate interval associated with the end of the last Ice Age. This "fossil" water is being used up faster than it is replenished and the water table is dropping over much of the aquifer except where substantial recharge occurs in areas of losing streams such as the Platte River, Nebraska, and from irrigation projects supplied by surface waters (Fig. 23).
The history of water use in the aquifer can be illustrated by reference to a single well in southwest Kansas (Fig. 24). The hydrograph (graph of water use) from the well illustrates three periods of groundwater withdrawal.

1. 1930-1950: water table depth remained relatively constant as withdrawal was limited to a few wells and kept pace with recharge.

2. 1950-1985: water table depth declined by 12 meters (40 feet) as increasing numbers of wells extracted water from the aquifer. Irrigated acreage in Kansas climbed from less than half a million acres in 1959 to nearly two million acres in 1978.

3. 1985 - present: decline in water table depth slowed considerably because of decreasing discharge attributed to heavier-than-normal rains, increased energy costs for pumping, and improved irrigation technology that consumed less water.

Groundwater from the aquifer was first widely used in the 1930s in Texas. Subsequently approximately 11% of the total groundwater supply has been extracted. The most significant declines in the aquifer have occurred in southwest Kansas and
the Texas Panhandle and have been matched by population migrations from rural counties.

Over the life of the aquifer the water table dropped 70 meters in parts of the Texas Panhandle (Fig. 25). Western Kansas has consumed 38% of the groundwater in the underlying aquifer. Both are examples of **groundwater overdraft** - where groundwater extraction occurs more rapidly than recharge. In

Figure 25. Map of groundwater level changes in the High Plains Aquifer prior to 1980. Map courtesy of USGS High Plains aquifer website.
contrast, Nebraska is blessed with more than 60% of the aquifer underlying the state, relatively good recharge from the Platte River, and less intensive groundwater consumption. Groundwater supplies in Nebraska are sufficient to last for centuries at current consumption rates.

**Think about it . . .**
You are given an assignment to help locate a new well field that will supply your town with water. You are asked to create your own evaluation rubric to evaluate at least five factors that will influence the availability of groundwater. The location that scores the highest using the scoring rubric will be selected for the well field. Go to the end of the chapter to complete the exercise.

**Human Modifications of Groundwater Systems**

- Excessive pumping of individual wells locally lowers the water table and creates a cone of depression around the well.
- Subsidence may occur when water is withdrawn from aquifers in unconsolidated materials causing pore spaces to collapse.
- Groundwater pollution may come from single-point sources or distributed non-point sources including agricultural fertilizers, landfills, oil wells, mines, septic tanks, road salt, and underground storage tanks.

**Local Overpumping**

Excessive withdrawal of groundwater at a regional scale may exceed recharge resulting in groundwater overdraft (see High Plains Aquifer section). Overpumping of individual wells will not permanently deplete an aquifer but can impact the use of neighboring wells. Pumping of a well pulls down the local water table adjacent to the well as water is withdrawn faster than it can be replaced (Fig. 26). The surface of the water table
forms a **cone of depression** surrounding the well. The change in elevation of the water table (**drawdown**) decreases with distance from the well. Given sufficient time, the water table will be restored to its original level when pumping stops. Domestic wells rarely yield sufficient water to generate a significant cone of depression but the large volumes of water necessary for irrigation can result in the formation of a sizable cone of depression around irrigation wells during the growing season.

The cone of depression for any single well may affect neighboring wells prompting landowners to ask who owns the water below their property? Nearly 50 years ago, Tom Bristor found out the hard way that the state of Arizona considered groundwater to belong to the person who could pump it out of the ground. (For more on Bristor's story see the box, Who Owns the Groundwater?)

**Ground Subsidence**

Groundwater removal from unconsolidated sediments may result in sediment compaction and the subsidence of the ground surface. The weight of the overlying material (including and any engineered structures) is supported by both the mineral grains and the water in the pore spaces in a confined aquifer. Pressure from water on the surrounding grains keeps the pore space open. When the water is extracted mineral grains may collapse inward on the pore space. This causes a decrease in the volume of the underlying sediment and can result in **subsidence** of the ground surface (Fig. 27). The Leaning Tower of Pisa, Italy, developed its characteristic tilt soon after construction began in 1174 because of subsidence following groundwater withdrawal. Subsidence of up to 9 meters...
occurred over an area of approximately 13,000 km² in the San Joaquin Valley, California, as a result of groundwater withdrawal for irrigation.

Cities built over weak unconsolidated fine-grained sediments associated with geologic environments such as floodplains, deltas, or lake beds often show evidence of subsidence (Fig. 27). Engineered structures (roads, pipelines, large buildings) may fracture or collapse as a growing city's population extracts increasing volumes of groundwater. Intensive pumping of over 500 million gallons of groundwater per day in the Houston region from 1967 to 1983 lowered the water levels in wells of the Texas coastal lowlands aquifer system. Water levels in the wells declined approximately 60 meters in the past 50 years, and are now more than 110 meters below sea level.

Groundwater Pollution

Natural groundwater is far from pure but it typically contains few chemicals in sufficient quantity to cause harm to humans and ecosystems. However, under specific geologic conditions, elements such as arsenic or mercury may be concentrated in groundwater. An example of widespread groundwater contamination by arsenic that may become the greatest mass poisoning in history is currently unfolding in the impoverished nation of Bangladesh. Over 20 million people may potentially be exposed to harmful levels of arsenic present in the country's four million groundwater wells. (For more on the Bangladesh arsenic crisis see the box, Arsenic and Bangladesh.)

Human development has added many potential pollution sources that may contaminate the groundwater supply. Pollution may be associated with specific identifiable point sources such as leaking storage tanks or may not be traceable to a single point of origin but may occur over a wide area (non-point source) such as croplands (Fig. 28).

The Clean Water Act (1972) and its amendments banned the most egregious examples of pollution from industrial point sources but many less obvious pollution sources still exist. The Woburn case cited in the Introduction is just one example. Other potential pollution sources in the U.S. include:

- approximately 3,000 landfills and thousands of illegal dumps that may leak a chemical soup of waste liquids;
• 23 million domestic **septic systems** that serve homes beyond the reach of municipal sewer systems;

• five million active and inactive **underground storage tanks** used to store products such as gasoline and industrial chemicals;

• over one million abandoned and active **oil and gas wells** that produce crude oil mixed with brines and water/mud mixtures;

• thousands of active and abandoned **coal and metal mines** many of which yield acidic runoff that percolates into the groundwater;

• thousands of tons of **animal wastes** concentrated in areas of livestock (chicken, pig, cattle) farms;

• millions of tons of **fertilizers, pesticides, deicing salts**, and other materials added to the land surface annually.

Non-point sources of pollution in agricultural regions are difficult to detect but can have some of the most far-reaching effects because rural well waters are not monitored by municipal water treatment plants. Pollutants that may be present in rural wells include pesticides (herbicides, insecticides, fungicides) and nitrates that are products of fertilizers. Both pesticides and fertilizers are applied to crops and some are washed off into the groundwater and surface water systems.

The Environmental Protection Agency (EPA) is responsible for enforcing water quality standards for drinking water. Some of the common pollutants that the EPA recognizes in drinking water are listed below.
<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Health Effect</th>
<th>Selected Sources</th>
</tr>
</thead>
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<tr>
<td>Organic Chemicals</td>
<td></td>
<td></td>
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<tr>
<td>Benzene</td>
<td>Cancer</td>
<td>Leaking fuel tanks, industrial solvent</td>
</tr>
<tr>
<td>Toluene</td>
<td>Kidney disease</td>
<td>Chemical manufacture, industrial solvent</td>
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<tr>
<td>Trichloroethane</td>
<td>Cancer</td>
<td>Dry cleaning and industrial solvent</td>
</tr>
<tr>
<td>Inorganic Chemicals</td>
<td></td>
<td></td>
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<tr>
<td>Arsenic</td>
<td>Cancer, skin lesions</td>
<td>Rocks, pesticides, industrial wastes</td>
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<tr>
<td>Nitrate</td>
<td>Blue baby syndrome</td>
<td>Fertilizers, feedlots, sewage</td>
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<td>Lead</td>
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<td>Corrosion of lead pipes</td>
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<td>Microbiological</td>
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</tr>
<tr>
<td>Cryptosporidium</td>
<td>Stomach illness</td>
<td>Human/animal wastes</td>
</tr>
</tbody>
</table>

**Think about it . . .**

1. Create a concept map that summarizes the characteristics of groundwater systems.
2. Use the Venn diagram found at the end of the chapter to compare and contrast the factors that control the flow of precipitation to streams vs. groundwater.
Who Owns the Groundwater?

The cone of depression for any single well may affect neighboring wells prompting landowners to ask who owns the water below their property. Nearly 50 years ago, Tom Bristor found out the hard way that the state of Arizona considered groundwater to belong to the person who could pump it out of the ground. Like many of his neighbors, Bristor drilled a shallow (50 meter) well to supply the domestic needs of his small ranch in southern Arizona. All was fine for nearly 20 years but in 1948 Bristor's well ran dry, forcing him to drill a new well to a depth of approximately 70 meters. He didn't have to look far to find the reason for his dry well. Bristor's neighbor, Armon Cheatam had been vigorously pumping water from 11 wells, several around 130 meters deep, to irrigate 2,000 acres of nearby desert.

The price for short-staple cotton had increased by 500% in the dozen years prior to 1950. By 1952 nearly half the cultivated land in Arizona was growing cotton, a notoriously thirsty crop that required extensive irrigation. Like many others, Cheatam sought to make some easy money using the apparently boundless groundwater resource under his feet. Cheatam's wells had created such an extensive cone of depression that they left Bristor's well stranded above the depleted water table.

Cheatam and Bristor found themselves on either side of a legal divide in the complex world of western water law. On the one hand was the view (Cheatam) that the landowner also possessed everything under the ground surface all the way to the Earth's core. In this view Cheatam could pump as much groundwater as his crops needed as long as the well was on his property. The opposing view (Bristor) followed the doctrine that rocks stay, water moves; essentially that a landowners can't own mobile groundwater any more than they own the air above their land. Bristor and his neighbors took Cheatam to court accusing him of unreasonable use of groundwater. The court eventually ruled in favor of Cheatam.

Arsenic and Bangladesh

Bangladesh is the most densely populated nation in the world with 124 million people living in an area about the size of Wisconsin. Unfortunately, Bangladesh is also one of the poorest nations in the world with little significant health care outside of the larger cities. Granted independence from Pakistan in 1973, most of Bangladesh's population is made up of farmers. Two decades ago most citizens obtained their domestic water from surface ponds and streams or shallow wells that were often contaminated by agricultural and industrial pollution. Hundreds of thousands of people died each year from diseases such as cholera and diarrhea contracted from drinking the polluted waters.

Beginning in the late 1970s, the United Nations sought to clean up the drinking water supply by providing materials for the 1,000,000 shallow (60-120 meter) water wells. Wells were installed in villages across the country and villagers brought water to the surface using a hand pump. So popular were the wells that residents drilled three million more wells into the near-surface aquifers for additional drinking water and for use in irrigation. Ninety-seven percent of Bangladesh's population now drinks well water. No one thought to test the well waters for natural pollutants.

Arsenic is present in the unconsolidated sediments that form the aquifers. Sediment was eroded from the Himalayas to the north from rocks with unusually high natural concentrations of arsenic. The sediment was transported south to Bangladesh, located on the world's largest delta complex where the Ganges and Brahmaputra Rivers enter the Indian Ocean.

Initial warnings about the dangers of arsenic poisoning (arsenosis) went unheeded in Bangladesh and the neighboring Indian Province of West Bengal. Many early symptoms of arsenosis were diagnosed as leprosy. The government of India was primarily concerned with the 17 million existing cases of tuberculosis and the 7 million people affected by diarrhea; it had few resources to devote to investigating reports of arsenic poisoning. Until the last few years there has been little concerted effort to determine the extent of the water...
contamination problem in Bangladesh or West Bengal.

The water quality standard for arsenic in drinking water is 50 ppb (parts per billion or 0.05 milligrams per liter) in Bangladesh (and the U.S.) but the World Health Organization (WHO) sets the standard at 10 ppb. Long-term exposure to arsenic shows up as skin lesions, spots, bumps and warts and after nearly a dozen years skin cancer may occur. Approximately 10% of those exposed will be affected by cancer of the lung, kidney, liver, or bladder after as much as 20 years. Arsenic-free water and a nutritious diet are necessary to halt the effects of arsenic poisoning if discovered during the early stages of the disease.

A World Bank survey of several hundred thousand wells has found 40% to be contaminated with arsenic. Estimates are that 20 to 60 million people in Bangladesh may be exposed to elevated arsenic levels in drinking water. The problem of water contamination would be solved in a more affluent nation by supplying those affected with bottled water or by drilling deeper wells. However, even such straightforward solutions are beyond the means of an impoverished nation like Bangladesh.

Sources:
Arsenic Project, Harvard University.
Introduction to Wetlands

- Federal programs encouraged destruction of wetlands during the 1800s but today seek to protect wetlands.
- Wetlands are identified by the presence of hydric soils, hydrophytic vegetation, and water on or near the ground surface.
- Most U.S. wetlands are freshwater wetlands but coastal wetlands are significant along the Gulf Coast.
- The benefits of wetlands include improvements in water quality, ecological habitats, reduced flooding, shoreline erosion control, and recharge for groundwater.

Characteristics of Wetlands

Our changing view of the role of wetlands illustrates the evolution of thought regarding the environment in the U.S. The same federal government that once encouraged the infilling of wetlands today joins with other nations as a signatory of the Ramsar Convention ("The convention on wetlands of international importance especially as waterfowl habitat") to preserve and protect wetlands around the world. Twelve Ramsar sites are distributed throughout the U.S., ranging from the northern rainforests of the Alaskan coast, to a Nevada desert oasis, to Florida's Everglades National Park.

Wetlands can carry an array of labels (e.g., bog, marsh, fen, swamps) depending on their specific conditions (Fig. 29) and may be covered by water all year or for just a few weeks. The Clean Water Act defines wetlands as, "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." Federal regulations identify wetlands by:

1. **Hydrologic conditions**: water must be present on the land surface, or soils in the root zone are saturated during the growing season or for longer periods.

2. **Hydrophytic vegetation**: specific plants that grow under wet conditions (e.g., cattails, wild rice, willows, sawgrass). An estimated 9% of all plant species in the U.S. and its possessions occur exclusively in wetlands.
3. **Hydric soils**: poorly drained (water-logged) soils that exhibit anaerobic (oxygen deficient) conditions during the growing season.

Wetlands can be divided into two general types:

- **Coastal wetlands**: 5% of current wetlands, including mangrove swamps, salt marshes, e.g., Louisiana Gulf Coast.

- **Freshwater wetlands**: 95% of wetlands including forested swamps, inland marshes, riparian (river) and lacustrine (lake) wetlands.

Nearly three-quarters of wetlands in the lower 48 states are on private land but federal regulations require that landowners get permission before altering wetland environments. The U.S. Army Corps of Engineers administers wetlands with the help of the Environmental Protection Agency (EPA). The Corps is authorized to issue permits to fill wetlands where projects are in the public interest. In an effort to ensure no net loss of wetlands such projects may be required to create an equivalent area of new wetlands for each acre of natural wetlands that is destroyed. The U.S. Constitution’s Fifth amendment states that private property may not be “taken” without “just compensation”. Some property-rights advocates have suggested that Clean Water Act regulations preventing the filling of wetlands represent a taking of private lands by the government; however, statistics show that projects that involve wetlands are rarely rejected by government agencies although they may undergo some modifications. In recent years the Corps has approved over 99% of all projects involving wetlands.

**Benefits of Wetlands**

Wetlands serve many positive functions in helping to regulate the natural environment. Wetlands can:

- **Figure 29. Two types of wetland: bottomland forested wetland (left) and fen with grasses. Images courtesy of U.S. EPA.**
• improve water quality by filtering out sediment and other contaminants;
• provide ecological habitats for migrating bird populations;
• provide breeding grounds for fish and shellfish, supporting commercial fishing operations;
• moderate the effects of flooding - slow runoff, especially downstream from urban centers;
• control shoreline erosion - act as a buffer for coastal storms;
• provide recreation - canoeing, hunting, fishing, bird-watching;
• act as recharge areas for groundwater systems.

Destruction of Wetlands

• Most U.S. wetlands are in Alaska.
• Wetland area in the lower 48 states has decreased by a little over half since the 1600s.
• Recently wetlands have been lost to agricultural and residential development.
• Hydraulic engineering projects have considerably altered the interaction between surface and subsurface water systems in southern Florida.
• Wetlands south of Lake Okeechobee have been replaced by sugar cane fields.
• Development in southern Florida has resulted in less groundwater recharge, salt water intrusion along the east coast, polluted runoff from sugar cane fields, and reduced habitats for fish, birds, and mammals.

Distribution of Wetlands

Wetlands cover approximately 103 million acres in the lower 48 states and an additional 170 million acres in Alaska. In the lower 48, Florida (11 million acres), Minnesota (9 million acres), and Texas (7.6 million acres) have the greatest areas of wetlands. Wetland areas have declined by approximately 55% since the 1600s in the U.S., outside of Alaska. California (91%), Ohio (90%), and Iowa (89%) have experienced the greatest proportional losses of wetland area.
Approximately 80% wetland losses in recent years (1985-1995) were the result of the agricultural draining of wetlands with the rest attributed to the draining and infilling of wetlands as a result of urbanization and development. The rate of wetland losses has declined from nearly 500,000 acres/yr in the 1950s to 117,000 acres/yr during the last decade.

Example: Florida Everglades

The Kissimmee River, Lake Okeechobee, and the Everglades are the key components of the largest drainage basin in southern Florida (Fig. 30). The Kissimmee River feeds Lake Okeechobee which supplies water that flows south through the Everglades, one of the world's largest freshwater wetlands. Marjory Stoneman Douglas termed the slow, unchanneled flow of water through the sawgrass prairie of the Everglades a “river of grass.” The bulk of the input of water into the Everglades is from precipitation (89%) with the rest is due to runoff. Most of the outflow occurs by evapotranspiration (66%).

Beginning in the early 1900s, development of southern Florida resulted in the construction of thousands of miles of canals that diverted water away from wetland environments (Fig. 31). Development proceeded with four goals (the 4 Ds): dike it, dam it, divert it, drain it. The result of this hydraulic engineering was greater flood control and expanded agriculture (Fig. 32). Although these were beneficial for landowners, development often had negative consequences for the local ecosystems. The original Everglades wetland system was largely a consequence of a combination of hydrologic

Figure 30. View of Florida peninsula from the Space Shuttle. Water flows down a gentle slope (3-6 cm/km) from Lake Okeechobee toward the Everglades. Original image courtesy of NASA's Earth from Space program.
conditions defined by the **hydroperiod** (duration of surface water) and **hydropattern** (depth of water). Water management practices associated with the expansion of farming and urban development altered flows in the Everglades and changed both the hydroperiod and hydropattern.

Some consequence of these changes were:

- channelization (straightening) of the **Kissimmee River** that destroyed wetlands and fish and wildlife habitat (Fig. 31);
- loss of transitional wetland habitat that provided feeding and nesting habitat for wading birds;
- polluted runoff from agricultural operations such as sugar-cane production (Fig. 32);
- decreasing soil formation and exposure of peat that results in fire hazard in dry periods (spring) or during drought conditions;
- salt water intrusion along the east coast;

Figure 31. Kissimmee River channelization project (1961). Note original channel meanders on either side of straightened channel. Image courtesy of South Florida Water Management District.

Figure 32. Changes in selected land use patterns in southern Florida from 1900 to 1973. Note the loss of wetland vegetation (sawgrass), growth of agriculture (sugar cane) and expansion of coastal cities.
less groundwater recharge and reduced flow of water to Florida Bay along the southern coast.

The creation of artificial wetlands is necessary because urban growth has destroyed natural wetland environments and population growth has placed greater demands on groundwater sources. Water demand in Broward County, Florida, increased by 40 million gallons per day from 1980 to 1990, as population increased by 200,000. The South Florida Water Management District has purchased thousands of acres of land to be used to enhance groundwater recharge in an effort to halt the decline of groundwater levels.

Summary

1. What is groundwater?
Groundwater is water stored in rocks or sediment below Earth's surface.

2. What is groundwater used for?
Nearly two-thirds of groundwater used in the U.S. is used for irrigation of crops in areas of limited precipitation. Groundwater is often used as a drinking water source in rural regions or in towns without a municipal water supply.

3. What is the hydrologic cycle?
The hydrologic cycle links the processes of evaporation, condensation, stream runoff, infiltration, percolation, and transpiration as water moves between the ocean, atmosphere, and land.

4. How long does water spend at each stage of the hydrologic cycle?
The residence time (time water remains in a given location) varies from an average of 4,000 years for the water in the
5. What rock properties are most important for groundwater? Rock type is important as rocks such as limestone may be dissolved by groundwater to form extensive cave systems. However, most rocks do not dissolve in groundwater but may allow water to flow through them (permeability) or store water in spaces (porosity) between grains (pores) or in fractures. These properties are most commonly developed in sediments or sedimentary rocks but can be present in other rock types under specific conditions.

6. How are porosity and permeability related to the grain size? Both porosity and permeability increase with increasing grain size. Larger grains result in larger spaces between grains (more porosity) and larger openings connecting the spaces (more permeability). Coarse-grained sediment (sand, gravel) and sedimentary rocks (sandstone, conglomerate) typically exhibit high porosity and permeability. Fine-grained materials (clay, mud, shale) are characterized by low permeability and porosity.

7. What is the difference between an aquifer and an aquitard? Aquifers are rock or sediment with good porosity and permeability that act as storage reservoirs for groundwater and allow the extraction of water by wells. Aquicludes are barriers to groundwater flow and are composed of rocks with poor permeability.

8. How do open and closed aquifers differ? Open aquifers are recharged with water that infiltrates downward from Earth's surface above the aquifer. There is no overlying aquitard to prevent water entering the aquifer by infiltration. In contrast, closed aquifers are overlain by aquicludes. A closed aquifer is replenished by recharge where the aquifer is exposed at Earth's surface. Closed aquifers are typically inclined rock units with groundwater flowing downslope from recharge areas of higher elevation.

9. What is the water table? The water table marks the top of the zone of saturation in an aquifer. Pore spaces are filled with water below the water table but are only partially filled above the water table (in the unsaturated zone). The water table will fall or rise depending on seasonal and annual variations in recharge.
10. Is the volume of groundwater constant?
No. First of all, groundwater is affected by climate cycles. Many groundwater systems in the western U.S. were filled when North America's climate was considerably wetter in the recent geologic past. Today, recharge occurs by infiltration of precipitation and outflow from (losing) streams. In wetter areas this is sufficient to maintain groundwater levels but in some areas in the relatively dry western states water tables have declined as recharge has lagged behind groundwater extraction. Natural outflow from groundwater systems occurs at springs, wetlands, (gaining) streams, and by oceanic discharge.

11. What is the High Plains aquifer?
The High Plains aquifer stretches from South Dakota to west Texas and covers an area of 480,000 square kilometers, making it the largest area of irrigation-sustained cropland in the world. The unconfined sand and gravel aquifer contains "fossil" water, the product of a wetter ancient climate associated with the end of the last Ice Age. There is no sufficient contemporary recharge source although substantial recharge does occur in some areas from streams and from irrigation projects supplied with surface waters.

12. Where and when does groundwater overdraft occur?
Groundwater overdraft occurs when groundwater extraction occurs more rapidly than recharge. Groundwater has been pumped too heavily in some parts of the Texas panhandle and southwest Kansas so that the water table has dropped as much as 70 meters taking groundwater beyond the reach of many wells.

13. Can the pumping of one well affect water levels in neighboring wells?
Yes. Pumping of a well lowers the local water table surrounding the well to create a cone of depression. With continued pumping, the cone of depression can expand outward, lowering the water table in adjacent wells.

14. How is groundwater extraction associated with ground subsidence?
The weight of the overlying material (rocks, trees, cities) is supported by both the mineral grains and the water in the pore spaces in a confined aquifer. If the mineral grains cannot bear the load alone they may collapse inward when the water is extracted. This causes a decrease in the volume of the...
underlying sediment and can result in subsidence of the ground surface.

15. Does most water pollution come from industrial plants? No, although this may have been the case several decades ago, water pollution may come from a variety of sources including landfills, septic tanks, underground storage tanks, mines, livestock compounds, and croplands. It is often difficult to determine the source of pollutants given the slow movement of groundwater and the indirect routes of groundwater flow. By the time pollution is detected the source may have been abandoned.

16. What features can be used to identify the presence of wetlands? Although the legal definition of wetlands can require a specific association of features, most geologists identify wetlands if they possess hydric (poorly drained) soils, hydrophitic vegetation, and water on or near the ground surface for weeks or months at a time.

17. Are there any benefits to the presence of wetlands? The benefits of wetlands include improvements in water quality, creation of ecological habitats, reductions in flooding, shoreline erosion control, recreation sites, and recharge zones for groundwater.

18. Where are most U.S. wetlands? Most U.S. wetlands are in Alaska. Florida, Minnesota, and Texas have the most wetland acreage in the lower 48 states.

19. Why were wetlands destroyed? In the last century and for much of this one, wetlands were thought to be breeding grounds for malaria and to have little value for other purposes. Consequently, wetlands were drained for agriculture or were infilled to allow the expansion of cities. The rate of wetland losses has declined over the last few decades as the potential benefits of wetlands have been recognized but there is still a net loss of wetlands. California and Ohio have lost the most of their original wetlands (90%).

20. How has development resulted in changes in the wetlands of southern Florida? Hydraulic engineering projects have considerably altered the interaction between surface and subsurface water systems in southern Florida. Wetlands south of Lake Okeechobee have
been replaced by sugar cane fields. Development in southern Florida has resulted in less groundwater recharge, salt water intrusion along the east coast, polluted runoff from sugarcane fields, and reduced habitats for fish, birds, and mammals.
U.S. Water Budget

Task 1: Examine the maps of precipitation and temperature and summarize their characteristics.

Task 2: Examine the maps of groundwater demand and rivers and summarize their characteristics.

Complete the table below to identify which parts of the U.S. have the greatest risk of future water shortages and which regions have a relatively abundant water supply. Identify regions by state or geographic region (e.g., Ohio and Indiana or the Midwest).

<table>
<thead>
<tr>
<th>Locations Where Conditions Favor a Reduction in the Supply of Freshwater</th>
<th>Locations Where Conditions Favor an Increase in the Supply of Freshwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absence or presence of rivers</td>
<td></td>
</tr>
<tr>
<td>High or low demand for groundwater</td>
<td></td>
</tr>
<tr>
<td>Low or high precipitation</td>
<td></td>
</tr>
<tr>
<td>High or low temperatures for evaporation</td>
<td></td>
</tr>
</tbody>
</table>
Future demand will also be dependent on population size. Using the map above identify cities that may have to take additional measures to supply their citizens beyond using local groundwater/streams. Explain why you believe these cities are at greatest risk.
Groundwater Systems Conceptest Questions

1. Liquid hazardous waste is disposed of by pumping it down injection wells. Examine the image below and predict which well location would be the most suitable to use for an injection well? Why?

   ![Diagram of groundwater system with wells A, B, and C]

   - **Well A** - Glacial deposits on hilltop
   - **Well B** - Shale bedrock
   - **Well C** - Sandstone bedrock
   - **Well D** - Glacial deposits in stream valley

2. The diagram below simplifies the potential groundwater sources for a location in northern Ohio. Which site would have the greatest groundwater production? Assume glacial deposits are sand and gravel.
   - a) A – Glacial deposits on hilltop
   - b) B – Shale bedrock
   - c) C – Sandstone bedrock
   - d) D – Glacial deposits in stream valley

   ![Diagram of groundwater system with layers labeled]

   - **Sediment**
   - **Sandstone**
   - **Shale**
Groundwater Rubric

You are given an assignment to help locate a new well field that will supply your town with water. In examining the potential sites you recognize that there are several different factors that can influence groundwater availability and none are optimum at any single site.

You are given the assignment to create your own evaluation rubric to evaluate at least five factors that will influence the availability of groundwater. The location that scores the highest using the scoring rubric will be selected for the well field. One factor is included as an example in the table below, identify five more.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Good (3)</th>
<th>Moderate (2)</th>
<th>Poor (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water</td>
<td>Shallow</td>
<td>Intermediate</td>
<td>Deep</td>
</tr>
</tbody>
</table>

Reviewing your evaluation rubric you realize that some factors are more significant than others. Your team decides to double the score of the most important factor. Which do they choose? Why?
Venn Diagram: Streams vs. Groundwater

Use the Venn diagram, below, to compare and contrast the factors that determine whether precipitation will enter streams or groundwater systems.