Water

In most parts of the world, water is a scarce resource. That might seem strange, because there is so much water on Earth. Almost all of the water on Earth, more than 97 percent of it, is seawater in the oceans. The rest is called fresh water, because it does not have a high salt content. Most of the world's fresh water is frozen solid in large glaciers in Antarctica and Greenland. Almost all of the fresh water that is available for human use is either contained in soil and rock below the surface, called groundwater, or in rivers and lakes.

Why is water an important resource?

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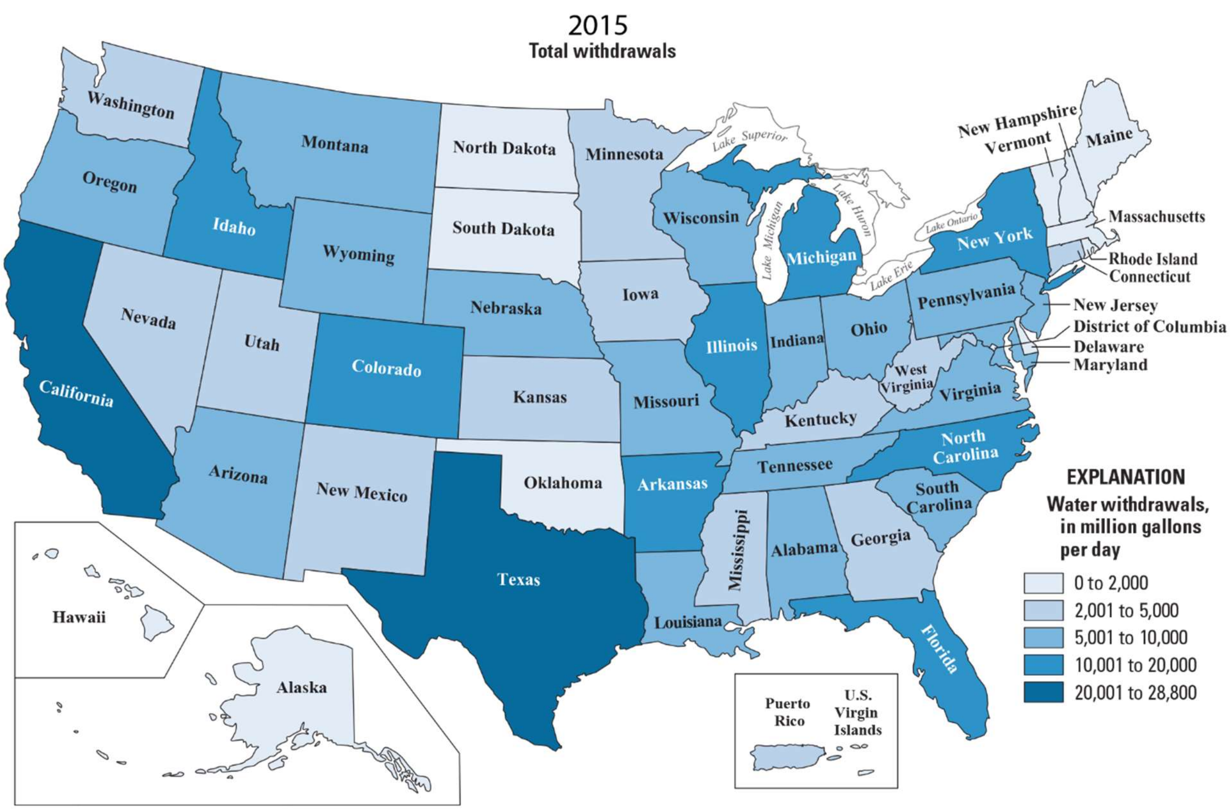

Figure 1. Water use by state. Credit: USGS, 2018.

In most areas of the United States, there is enough fresh water for human use. Yet usable fresh water is not as abundant as you might think. In some areas, like the arid Southwest, there is not enough water. In those areas, water must be transported long distances from other places in human-made channels called aqueducts. Even in areas with plenty of fresh water, there are sometimes shortages. Rainfall is the only way that water supplies are replenished. During times of drought, when rainfall is below average for a few years, water supplies can become dangerously low. Even when rainfall is adequate, water from rivers and lakes might be unusable because of pollution. In some areas, groundwater cannot be used because when it is removed from the ground, nearby wetlands would be damaged by drying up. As the population of the United States continues to grow in the future, water shortages will become more common, because the supply of available water remains the same. Water conservation will become more and more important as time goes on.

People use water in many ways at home: drinking, cooking, bathing, brushing teeth, washing clothes, dishes, and cars, flushing toilets, watering gardens and lawns, and filling swimming pools. Most people do not think much about how much water they use. Perhaps this is partly because they don't pay for it each time they use it, except when they buy bottled water.

There are many ways to conserve water in homes. Some are easier than others. Leaky faucets and leaky toilets waste very large amounts of water, because even though the flow rates are small, they leak all the time. New designs of toilets and washing machines use much less water than older designs, but replacement is expensive. Water-saving shower heads save a lot of water, and they are relatively easy and inexpensive to replace. The most effective ways to reduce water use, however, might be the most difficult. Taking "navy showers" (turning off the water while you're soaping yourself), not planting lavish lawns in areas that are normally arid, and not washing cars so often are examples of effective and simple ways to conserve water.

How is water distributed?

In rural areas, most homes and businesses get their water from groundwater. Long ago, wells had to be dug by hand and reached only shallow groundwater. Now wells can be drilled by machinery to as deep as several hundred feet. In urban and suburban areas, most water is piped in from a central water supply. The water supply might be a river, a natural lake, a reservoir behind a dam, or a number of deep wells. In many big cities, reservoirs are located far away, and the water is brought to the city through aqueducts.

If you have ever tried to stop the flow of water from a hose or pipe, or if you have seen a hose or a pipe burst, you know that water pressure is very high. The high pressure ensures that the flow of water is adequate wherever and whenever it is needed. Storing water at a high elevation in a lake or reservoir can produce pressure. Where water is pumped from the ground it is stored in special tanks on hilltops. In home water systems pumps produce the pressure needed.

Figure 2. The Hoover Dam, located on the Colorado River t the border between Arizona and New Mexico. Credit: M. Collier.

In urban and suburban areas, water is distributed from the source through large underground pipes. A map of the water mains in your town would look something like the pattern of branches on a tree or tributaries in a river system. The water mains keep branching out into smaller and smaller pipes until they reach homes or buildings, where they enter the building and pass through a water meter. In areas with cold winters, mains and pipes have to be buried several feet below the surface to keep them from freezing.

Most of the water that is used inside homes or schools flows through drainpipes into a municipal sewer system or into a septic system connected to the building. A septic system consists of a large tank buried in the ground. The solids in the sewage are slowly digested by microorganisms and converted to sludge. The sludge settles to the bottom of the tank and is pumped out occasionally by special trucks. The wastewater flows out of the tank and into underground pipes that leak water into the ground over a large area.

Municipal sewer systems collect used water and carry it through a network of underground pipes to a central treatment plant. Some treatment plants only filter out solid materials, while others treat sewage in several stages and end up with water that is pure enough to drink! The treated sewage is usually returned to rivers, lakes, or the ocean, or is spread on the ground to soak in. In some places untreated (“raw”) sewage, is still dumped directly into rivers, lakes, or the ocean.

Some of the water that is used in homes and schools evaporates. Most of the evaporation happens when water is spread over a large area, as in cleaning floors or pavement, or in watering a lawn or garden.

Figure 3. Water drainage through watersheds. Credit: M. Collier.

Where does our water come from?

Everybody knows that water flows downhill. The reason is that the force of gravity pulls everything downward toward the center of the Earth. If a material is resting on a sloping surface, part of the force of gravity acts in the downslope direction. If that does not make sense, think about leaning a board against a wall at an angle and placing a brick on the board. You need to exert a force to keep the brick from sliding down the board. The steeper the board, the more force you have to exert to keep the brick from sliding. Groundwater flows from high areas to low areas also, but its motion is much more difficult to observe. Water in the pipes in homes can flow upward as well as downward, because the high pressure in the pipes is much greater than the force of gravity.

The source of almost all of the water supplies for human civilization is rainfall or melted snowfall. When rain falls on the land, it either runs off into streams and rivers or it soaks into the ground to become groundwater. The groundwater flows slowly underground, and eventually comes back out to the surface at the beds of lakes and rivers.

Every stream or river drains a particular area of the land surface. The land area that is drained by a given river is called the watershed of that river. Watersheds are also called drainage basins. The imaginary line on the land surface that separates the watershed of one river from the watershed of another river is called a divide. Divides follow along the crests of hills and ridges. You can stand on a divide and pour a glass of water from one hand into one watershed and a glass of water from the other hand into another watershed! There are watersheds for groundwater as well as for surface water. Divides between groundwater drainage basins are usually in about the same place as divides between river drainage basins.

Most towns and cities get their water from their own watershed. In some places, especially in large cities, the demand for water is greater than the supply in the local watershed. Then water has to be transported from distant watersheds.

How is water recycled in nature?

Water exists at the Earth's surface as liquid, solid, and vapor. It is forever changing from one of those three states to another. You can easily observe how water changes from liquid to solid by freezing and from solid to liquid by melting. Water also changes from liquid to vapor by evaporation and from vapor to liquid by condensation. Condensation is how clouds and raindrops form. Water can even change from vapor directly into solid; that is how snowflakes are formed, high in the atmosphere.

The total amount of water near the surface of the Earth stays almost the same through time, but water is always moving from place to place. You can think of places where water resides, like the ocean or lakes or glaciers, as “reservoirs.” Water moves from reservoir to reservoir in various ways. It can move in the form of liquid, solid, or vapor. This complicated movement of the Earth's water is called the water cycle. Storms move out of the Gulf of Alaska into the Pacific Northwest region of the continent with great regularity, as many as three or four per week during the height of the winter storm season.

One of the most important “loops” in the water cycle involves evaporation of water from the ocean surface, transport in the form of water vapor to the continents by winds, and precipitation as rain or snow on the continents. The rainfall then runs off by way of streams, rivers, and groundwater back to the ocean. You modeled a similar loop with your distillation set up. Another important “loop” in the water cycle involves condensation of water vapor in the atmosphere to form rain, soaking of the rain into the ground, uptake of the water by plant roots, and return of that water, in the form of water vapor, back into the atmosphere by transpiration through the leaves of the plants. There are many other “loops” as well. The Earth's water cycle is very complicated in its details.

What is ground water flow?

Most of the materials beneath the Earth's surface are porous meaning they contain tiny open spaces. The porosity of a material is the percentage of open pore space it contains. Loosely packed sand and gravel can have porosities as high as 25 percent. Solid rock is much less porous. Many rocks have a porosity of only a small fraction of a percent.

Another important property of Earth materials is their permeability. The permeability describes how easy it is to force a fluid to flow through the pore spaces of the material. Loose sand and gravel have high permeability. Solid rock usually has low permeability. The best sources of ground water, called aquifers, have high porosity and also high permeability. Sand, gravel, and fractured rock make the best aquifers.

Ground water flow is much slower than flow in streams and rivers. That is because the passageways through the pore spaces are very small, so there is a lot of friction with the solid walls of the pores. Speeds of flow in streams and rivers are often greater than a meter per second. Ground water flow is often as slow as meters per day.

For a large town or city to obtain its water from ground water, there needs to be a large aquifer. Several widely spaced wells are used to pump water from the aquifer, all at the same time. If the ground water is replaced as fast as it is pumped, then it is a renewable resource. If the ground water is pumped faster than it is replaced, however, then the level of the ground water falls. It becomes more and more difficult to obtain the needed water. Then the ground water is not really a renewable resource, because the replacement might take far longer than a human lifetime!

Why is water special?

You probably take water for granted because it is so common, but water is a very unusual substance. Its most spectacular property is that ice floats in water. You probably think that's no big deal, but water is almost the only substance in the universe for which the solid floats in the liquid! Water is very unusual in several other ways as well. For example, the heat capacity of water is higher than just about any other substance. The heat capacity of a substance is the amount of heat you need to add to a mass of material to raise its temperature by a given amount. The heat capacity of water is more than twice the heat capacity of natural mineral and rock material. This tends to even out temperature differences on Earth, from day to night and from summer to winter. Water is also the best all-around solvent. More solid substances dissolve in water than in any other liquid.

Water consists of molecules with the composition H_2O (two small atoms of hydrogen and one larger atom of oxygen). The two hydrogen atoms are bonded very strongly to the oxygen atom. The three atoms are not arranged in a straight line; instead, they form an angle. The electrons that orbit around the three atoms are more strongly attracted to the oxygen atom than to the hydrogen atoms. Electrons have a negative electric charge. This gives the oxygen “side” of the water molecule a slightly negative electric charge. The hydrogen “side” of the water molecule has a slightly positive electric charge. Molecules like this, with one side positive and the other side negative, are called polar molecules.

In nature, electric charges of the same sign repel, and electric charges of different signs attract. When water molecules bond together in a regular structure to form solid ice, the positive sides of the molecules are attracted to the negative sides of adjacent molecules. The bond that is formed is called a hydrogen bond. It is weaker than the bonds between the hydrogen and the oxygen but still strong enough to cause water to freeze into ice.

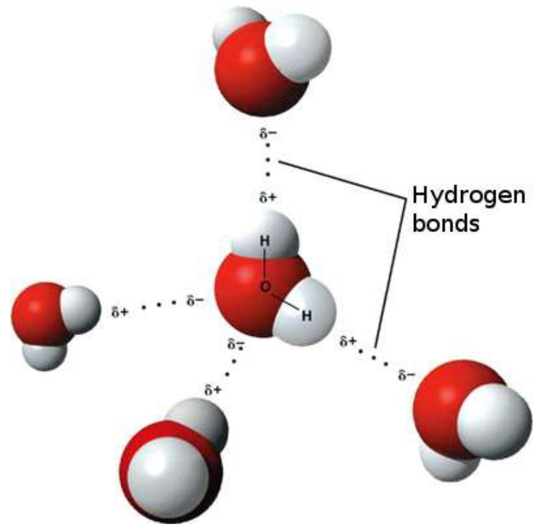

Figure 4. Interactions between four water molecules. Credit: CC BY-SA.

Why does ice melt when the melting temperature is reached? In nature, every atom or molecule undergoes a vibration, or "jiggling," because it has thermal energy. The strength of the vibration increases with temperature. When the temperature is high enough, the ice melts, because the thermal vibration of the molecules becomes so strong that the hydrogen bonds are broken. In the ice structure, the molecules have a relatively open arrangement. When the ice melts, the molecules become free to pack together more closely. That is why water is denser than ice.

The water molecules in liquid water attract each other. Inside the liquid, any particular water molecule is acted on by attractive forces from all directions. It is different for a molecule right at the water surface, however. It is attracted by molecules below it and beside it, but not from above. This makes the surface tend to shrink parallel to itself. This shrinkage force is called surface tension. Have you ever watched a soap bubble being made by waving a bubble wand? It's stretched out at first, but as soon as it leaves the wand, it becomes a sphere. That is because surface tension is making the whole bubble pull inward on itself.

The rise of water in a thin tube is called capillary action. It is another effect of surface tension. The surface of water in the tube curves upward around its edge. (This curved surface is called the meniscus.) To understand capillarity, you need to know that there is more to surface tension than just at the water surface. There is also surface tension in the film of water that is contact with the glass of the tube, and also in the film of air that is in contact with the glass of the tube. The surface tension of the air film is stronger than the surface tension of the water film. That causes the meniscus to be pulled upward along the glass surface, and water rises up in the tube. Capillarity explains why a piece of cloth or a paper towel gets wet when you hang its lower edge in water. The tiny passageways between the fibers act as capillary tubes! When the material is treated with a water repellent, the surface tension between the air and the material is reduced. Then water is no longer is drawn up into the fibers.

What is "good" water?

Figure 5. Testing water quality can ensure it is safe for drinking. Credit: Center for Disease Control (CDC).

The term "water quality" is used to describe how good a water source is for human use. The idea of water quality would be easy to deal with if all water sources were either "good" or "not good". The real world is more complicated than that. There are all degrees of "goodness" of water. That is because many substances can affect water quality, and their concentrations can range from very low to very high. The quality of water required also depends on its intended use. For example, the quality of water that is meant for drinking ("potable" water) is different from the quality of water that can be used irrigation of fields.

What are pollutants?

Some of the substances that affect water quality are called pollutants. Pollutants are mostly substances that get into water by human activities. The number of toxic chemicals that are produced and used by humans is enormous. Many of these toxic chemicals are used in ways that cause them to be added to surface water or ground water. Here are two major examples:

1. Gasoline at filling stations is stored in large tanks underground, beneath the pavement. Old tanks sometimes become corroded and leak gasoline into the ground. The gasoline does not mix directly with the water, but small concentrations dissolve in the water.
2. In the past, factories that used toxic substances often dumped the wastes directly into rivers, lakes, and estuaries. These substances tend to become attached to sediment particles. They remain in the area indefinitely. They then gradually enter the water in small concentrations.

Figure 6. Pollutants can enter water from many sources. Credit: Environmental Protection Agency (EPA).

Cleaning up sources of pollution like these takes enormous sums of money. All of the contaminated soil or sediment has to be removed. Sometimes it is just put in special places that are sealed off from the environment forever. Sometimes the toxic substances are converted into nontoxic substances by chemical processes. Have you ever thought about what happens to the salt that is put on roads in winter in the northern areas of the United States? It is dissolved by later rainfall. Some of it enters rivers and is carried to the ocean, and some of it is added to ground water. Pollution by road salt is a major problem in some watersheds

How does water become polluted?

Many substances that are hazardous to human health can enter water supplies. Chemical waste from factories is sometimes dumped into rivers and lakes, or directly into the ground. Pesticides (chemicals that kill insects) applied to farmland enter surface water and groundwater, often in large quantities. Leaks from underground storage tanks for liquids like gasoline go directly into groundwater. Salt put on icy roads in winter pollutes water also, although it is not as hazardous to health.

Once a pollutant enters a water supply, it is difficult to get rid of it. Some pollutants slowly break down into harmless chemicals. Once the input of pollution is stopped, the pollutant gradually travels downstream and is replaced by unpolluted water. The problem is that it usually takes a long time for pollution to clear up in that way. As the pollutant travels downstream it is diluted by the addition of water. This causes the concentration of the pollutant to decrease. Often the concentration becomes low enough for the water to be judged safe for use, but the pollutant is still there.

Figure 7. A river contaminated with waste. Tim McCabe, courtesy of USDA NRCS.

What are harmful microorganisms?

Microorganisms that cause illnesses also affect water quality. Bacteria are single-celled organisms that cannot be seen with the human eye except through a microscope. Some kinds of bacteria are the most dangerous microorganisms. They usually get into water supplies when untreated sewage mixes with the water supply. It is not only a matter of human wastes from leaky sewer pipes. Dog and cat droppings are also deposited on land inside and outside the city.

Figure 8. Algal blooms can harm water quality. Credit: Keane.

What are natural solutes?

Naturally occurring substances also affect water quality. Even raindrops are not pure water. As they fall, they pick up tiny dust particles and also harmful substances like acid that are in the atmosphere. When the rainwater comes in contact with soil and rock material, some of that material dissolves in the water. Substances that are dissolved in water are called solutes. The concentration of natural solutes depends mainly on two factors: the composition of the soil and rock material, and how long the water is in contact with that material. Calcium makes water "hard," although not harmful. Hard water has a noticeable taste, and it can leave deposits inside pipes and tanks. The softest and purest water comes from areas that are far from where humans live, and have rock like granite or quartz sandstone that does not dissolve easily in water.

How is water cleaned and tested?

Most people in the United States get their water from municipal (city and town) water systems. Most people in rural areas, and some also in suburbs, get their water from their own wells, which tap shallow or deep groundwater. The water that is supplied from municipal water systems comes mainly from three sources: streams and rivers; natural lakes or artificial reservoirs; and ground water, pumped from large wells. Lakes and reservoirs that are located in unpopulated areas far from cities and towns usually have the highest-quality water. That is true also for streams and small rivers in unpopulated areas. Large rivers usually have lower-quality water, because of pollution from upstream areas. Ground water is contained in underground materials called aquifers. The quality of ground water varies a lot from place to place, depending on the quality of the surface water that supplies the aquifers.

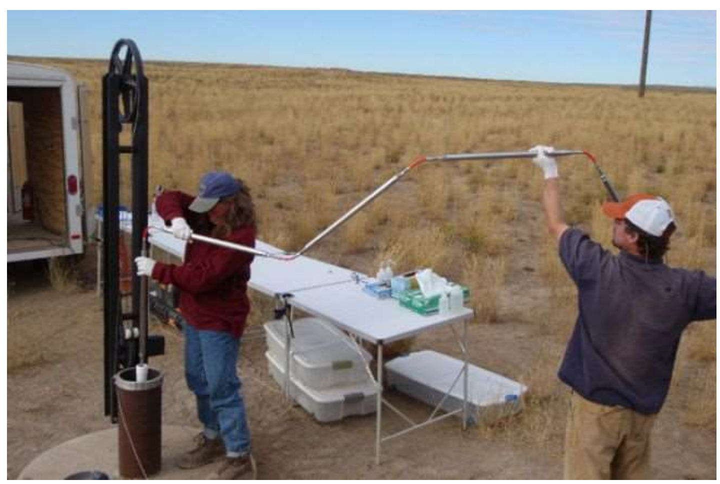

Figure 9. Water is tested before a new well is drilled. Credit: USGS.

How is drinking water cleaned?

Some sources of drinking water are of such high quality that not much treatment is needed. Usually adding small amounts of chlorine is sufficient to kill any harmful bacteria or other microorganisms. Other water sources, especially large rivers, have higher levels of

Figure 10. Water-processing plant. Credit: iStock

pollution. Such sources require more to bring the water up to the needed level of quality. River water usually contains fine sediment particles in suspension. The water can be passed through filtration materials, like sand, to remove the fine sediment. Filtering the water also tends to remove bacteria. Another way of removing the fine sediment is to let the water sit in large basins while the sediment slowly settles to the bottom. Sometimes this settling process is speeded up by adding certain chemicals that cause the fine sediment particles to clump together into larger particles. The larger particles settle faster than the original fine particles.

One problem in any system for water treatment is the difficulty of removing dissolved salts. All natural waters contain some dissolved substances, like sodium, calcium, magnesium, and iron. When the concentrations are too high, however, the water may taste salty. Calcium and magnesium make the water "hard," which makes washing with soap or detergents more difficult. Salt can be removed from water by various processes in what are called desalination plants. Drinking water produced by desalination is considerably more expensive than natural fresh water. It is used mainly in developed countries, like the United States , Israel , and Saudi Arabia , where fresh water is scarce but the ocean is nearby. Some coastal cities in California are beginning to use desalination for part of their water supply.

How is wastewater cleaned?

Most of the water that is used in homes and businesses is put into either municipal sewers or home septic systems. Most of that water is polluted to some extent, because it comes from clothes washing, bathing, and toilets. In earlier times, sewage was put directly into the ground, into rivers, or into the ocean, without any treatment. As population has grown, however, the need for wastewater treatment has increased as well.

Home septic systems consist of a large underground tank, where anaerobic bacteria (those that do not need oxygen) gradually break down most of the solids. The remaining liquid waste flows out into what is called a leach field, where the water flows out from porous underground pipes into the ground. This water still contains pollutants and harmful microorganisms. Some of these are removed as the water flows through soil and rock, but in many places they reach groundwater supplies and add to problems of water pollution.

Municipal sewage is treated in special wastewater treatment plants. There are several common methods of treatment. Also, the level of treatment varies greatly.

- In primary treatment, all that is done is to put the water in large tanks or ponds to let the solid material, called sludge, either float to the surface or settle to the bottom. The water is then usually chlorinated, and the sludge is treated and disposed of in various ways.
- Most wastewater undergoes secondary treatment as well as primary treatment. The most common method is to sprinkle or trickle the water over a bed of sand or gravel. As the water filters downward, it is put into contact with oxygen and microorganisms, which work together to break down the organic matter in the water. The water is then usually chlorinated before it is released into the environment.
- In a few places, the water undergoes tertiary treatment, which involves a variety of processes to purify the water even further. After tertiary treatment, the water can be pure enough to drink!