Chapter 7: Understanding Water

Ice floating in the ocean. *Image source*: Microsoft Stock Images

"Thousands have lived without love, not one without water."

Wystan Auden

"Whiskey is for drinking. Water is for fighting."

Mark Twain

"No water, no life. No blue, no green."

Sylvia Earle

Learning Objectives

By the end of this chapter, students will be able to:

1. Draw multiple interacting water molecules and identify the atoms and bonds.
2. Explain how the molecular structure of the water contributes to the unique properties of water.
3. Demonstrate an understanding of how much freshwater is available on Earth and how it is distributed.
4. Name the major pools (stores) in the water cycle and explain their roles.
5. Explain how human modifications of natural water systems can be both beneficial and destructive.
6. Explain the components of groundwater.

Contents

7.1 Introduction

Why do scientists spend a lot of time looking for water on other planets? Why is water so important that we have to keep looking for it? Water is one of the most abundant substances on Earth and also one of the molecules critical to life. Approximately 70 percent of the human body is made up of water. Without it, life as we know it simply would not exist as is humbly expressed by Sylvia Earle's quote above. The quote attributed to Mark Twain (see chapter title page), suggests that water is extremely important and worth more than whiskey. In fact, some scholars claim that water is worth more than gold and silver. To further highlight the significance of water is the quote from Wystan Auden that we can live without love but not without water. The value and importance of water is reflected in the frequent water related conflicts and disputes worldwide. Fortunately, most conflicts end up in the courts instead of the battlefields. This chapter is devoted to understanding the properties, availability, cycling, and distribution of this precious resource that sustains our planet and all known living things.

The importance of water to life is demonstrated by the numerous descriptions associated with water such as "the essence of life", "blue gold" and "more precious than oil". What makes water so unique and invaluable to life is its special properties that are attributed to its molecular structure. These special properties include a high specific heat capacity, high heat of vaporization, ability to dissolve numerous polar molecules, its cohesive and adhesive properties, and the ability to dissociate into ions (that leads to the generation of pH). Understanding these characteristics helps us comprehend and appreciate its importance in maintaining life on Earth. Before we discuss these properties, let's review the molecular structure of water, which gives rise to these special properties.

7.1.1 The Structure of Water Molecules

A single water molecule is composed of two atoms of hydrogen attached to one atom of oxygen by covalent bonds (H_2O). Covalent means that atoms share electrons and must, therefore, stay together. This is not the same as ionic bonding in which atoms are attracted to one another due to opposite charges that result when each atom completely gives up electrons to or gains electrons from another. When the sharing of electrons among the atoms is equal, for example two atoms of oxygen sharing electrons to form oxygen gas (O_2), the bond is known as **non-polar covalent bond**. Unequal sharing of electrons occurs when one atom has a stronger "pull" on the electrons, resulting in a **polar covalent bond**. A polar molecule, therefore, has one end that is slightly negative and another that is slightly positive – like the opposite poles of a magnet – because the electrons are not shared equally between its atoms. In the case of water, the single oxygen atom is considerably larger (more electronegative) than the hydrogen atoms, making it more likely that a shared electron would be found closer to the oxygen nucleus than the hydrogen nucleus.

7.1.2 Water's Polarity and Hydrogen Bonding

Water is a **polar** molecule, meaning it has regions with slight electrical charges due to the unequal sharing of electrons between its atoms. In each water molecule (H_2O), the larger oxygen atom attracts electrons more strongly than the hydrogen atoms. As a result, the oxygen end becomes slightly negative (δ–), while the hydrogen ends become slightly positive (δ+). This uneven distribution of charge gives water molecules a bent shape (**Figure 7.1**) and causes them to act like tiny magnets where the positive side of one water molecule is attracted to the negative side of another. These attractions are called **hydrogen bonds** (**Figure 7.1**) and form between different water molecules. Although each hydrogen bond is weak on its own, the combined effect of many hydrogen bonds gives water its unique and vital properties which are discussed in the next section. Hydrogen bonds can form between different molecules and they do not always have to include a water molecule. Hydrogen atoms in polar bonds within any molecule can form bonds with other adjacent molecules. For example, hydrogen bonds hold together two long strands of DNA to give the DNA molecule its characteristic double-stranded structure.

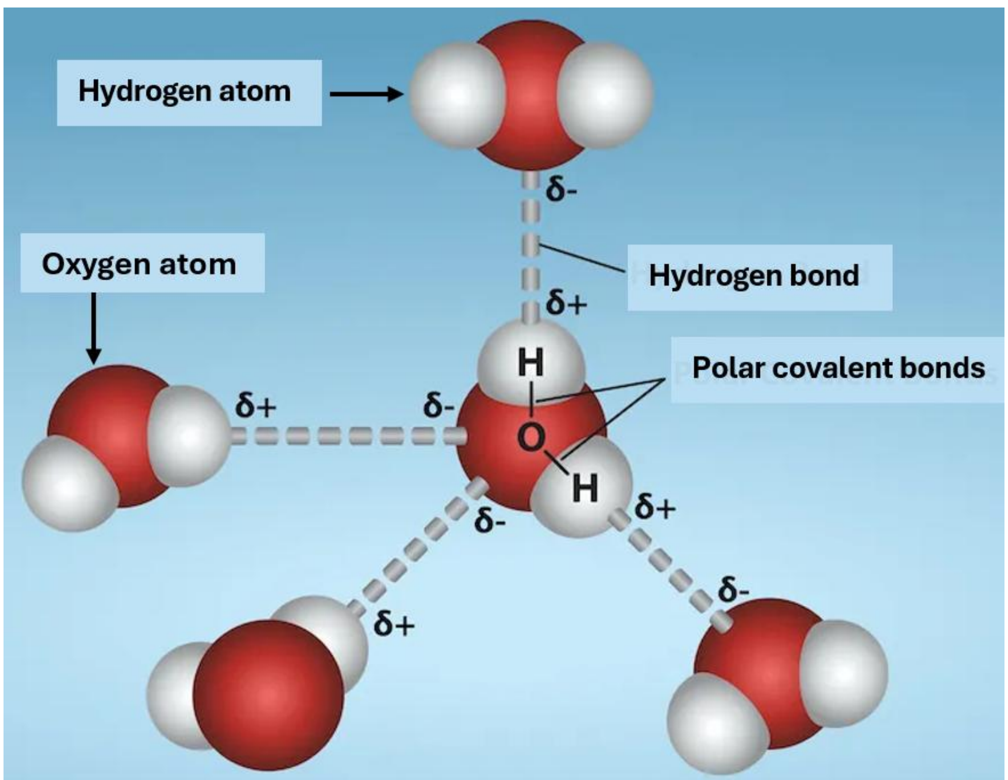

Figure 7.1. The polarity of water is due to the differing electronegativities of hydrogen and oxygen. As a consequence, hydrogen bonds are formed when the slightly negative oxygen on one water molecule is attracted to the slightly positive hydrogen of another water molecule. (From OpenStax Biology 2e text)

Water also attracts or is attracted to other polar molecules and ions. We call a polar substance that interacts readily with or dissolves in water **hydrophilic** (hydro- = "water"; -philic = "loving"). In contrast, nonpolar molecules such as oils and fats do not interact well with water. A good example of this is vinegar and oil salad dressing (an acidic water solution). We call such nonpolar compounds **hydrophobic** (hydro- = "water"; -phobic = "fearing").

Test your knowledge…

THAT'S SO POLAR!

1. *What two elements make up a single water molecule, and how many atoms of each element are there?*
2. *What type of bond holds together the atoms within a single water molecule?*
3. *Why are water molecules described as polar?*
4. *Which atom in a water molecule has a stronger attraction for shared electrons?*
5. *What are the partial charges (negative or positive) on the oxygen and hydrogen atoms in water?*
6. *Do hydrogen bonds form within or between water molecules?*
7. *How many hydrogen bonds can a single water molecule form?*

7.2 Properties of Water

Water exhibits a set of unusual and essential characteristics that distinguish it from most other substances. These distinctive behaviors stem from the structure of the water molecule and the hydrogen bonds that form between neighboring molecules as explained in sections 7.1.1 and 7.1.2. Although an individual hydrogen bond by itself is weak, the sheer number of them creates collective effects that shape how water behaves in natural and biological systems. Understanding these properties provides the foundation for explaining many biological processes that support life and environmental processes that we depend on.

7.2.1 The Physical State of Water

Water on Earth can naturally exist in three states of matter, **solid**, **liquid** or **gas**, depending on the prevailing temperature and pressure conditions. Majority of water on Earth's surface exists in liquid form which is one of the reasons why Earth can support life. When heat is added to liquid water (increasing temperature), the **kinetic energy** of the molecules goes up and helps to break up the hydrogen bonds. As more heat is added to boiling water, the higher kinetic energy of the water molecules causes the hydrogen bonds to break completely and allow individual molecules to escape into the air as water vapor (**gas**). On the other hand, when the temperature of liquid water is reduced and water freezes, water molecules form a crystalline structure maintained by hydrogen bonding (since there isn't enough energy to break the hydrogen bonds). The crystalline structure is formed when water molecules arrange themselves into a structured, orderly pattern called a **lattice**. You can think of it like a three-dimensional honeycomb or a connected network of molecules holding hands (**Figure 7.2**). The open structure of ice makes ice less dense than liquid water. Water therefore is denser as a liquid and less dense as a solid, a phenomenon not seen in the solidification of other liquids.

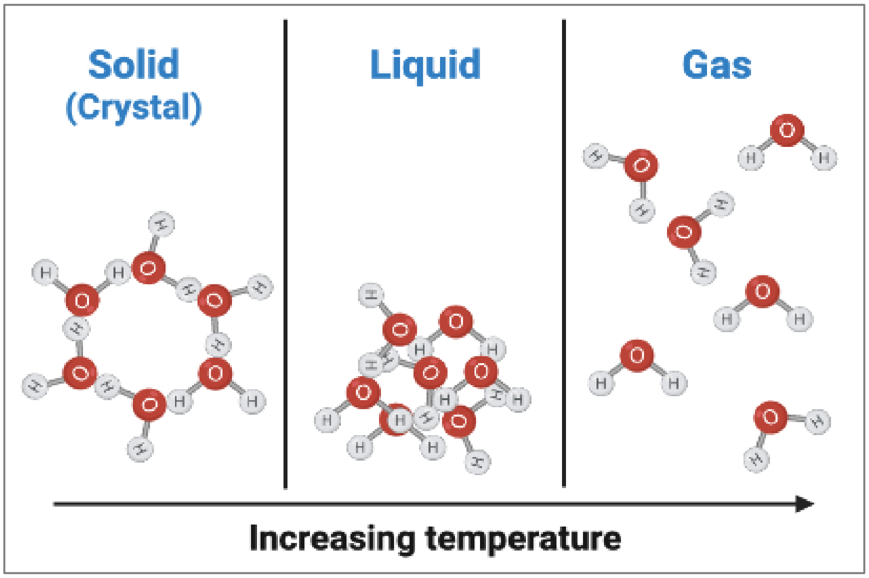

Figure 7.2. Hydrogen bonding makes ice less dense than liquid water. The lattice structure of liquid water is more condensed (middle structure) than that of ice (left structure). The lattice structure of ice makes it less dense than freely flowing molecules of liquid water, enabling ice to float on liquid water. (Image credit: Steve Jessup)

The lower density of ice, illustrated in **Figure 7.2**, causes it to float on the surface of liquid water. This phenomenon is exemplified by icebergs in the ocean (like the image on the chapter title page) and ice cubes in a glass of ice water. When lakes and ponds experience freezing temperatures the top water molecules will cool first and form ice. Since ice is less dense than liquid water, the ice will stay on the surface of the pond creating an insulating barrier that keeps the water below in liquid form. This in turn protects animals and plants (that live in the water) from freezing over. Without this layer of insulating ice, the entire water column would freeze killing most plant and animal life. The ice crystals that form upon freezing would rupture the delicate membranes essential for the function of living cells, irreversibly damaging them.

7.2.2 High Specific Heat Capacity

Specific heat is defined as the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius (°C). Water has the highest **specific heat capacity** of any substance that naturally exists as liquid at room temperature and pressure. For water, this amount is one **calorie**. Other substances have lower heat capacities compared to water: oil = 0.4 calorie, alcohol = 0.57 calorie, dry soil/sand = 0.19 calorie, wood = 0.14 calorie, iron = 0.11 calorie. For example, because iron's specific heat capacity is only 0.11 calories per gram, adding just 1 calorie of heat raises the temperature of 1 gram of iron by about 9°C, which is much more than the 1°C increase in 1 gram of water, illustrating how unusual water's heat-holding ability is. Water's high specific heat capacity arises from the energy needed to disrupt its extensive network of hydrogen bonds. Much of the heat added to water is first used to break these bonds rather than directly increasing molecular motion, allowing water to absorb or release large amounts of heat with only small changes in temperature. For example, because the specific heat capacity of water is about five times more than that of sand, dry sand at the beach heats up faster than the water but is also cools down faster than the water.

Hydrogen bonds also give water a **high latent heat**; the heat required to undergo a phase change from solid to liquid, or liquid to gas (**Figure 7.3**). The **latent heat of fusion** is the heat required to go from solid to liquid; 80 cal/g in the case of ice melting to liquid. Ice is a solid because hydrogen bonds hold the water molecules into a solid crystal lattice (shown in **Figure 7.2** in section 7.2.1). As ice is heated, the temperature rises up to 0°C. At that point, any additional heat goes to melting the ice by breaking the hydrogen bonds, not to increasing the temperature. So, as long as ice is present, the water temperature will not increase. This is why your drink will remain cold as long as it contains ice; any heat absorbed goes to melting the ice, not to warming the drink.

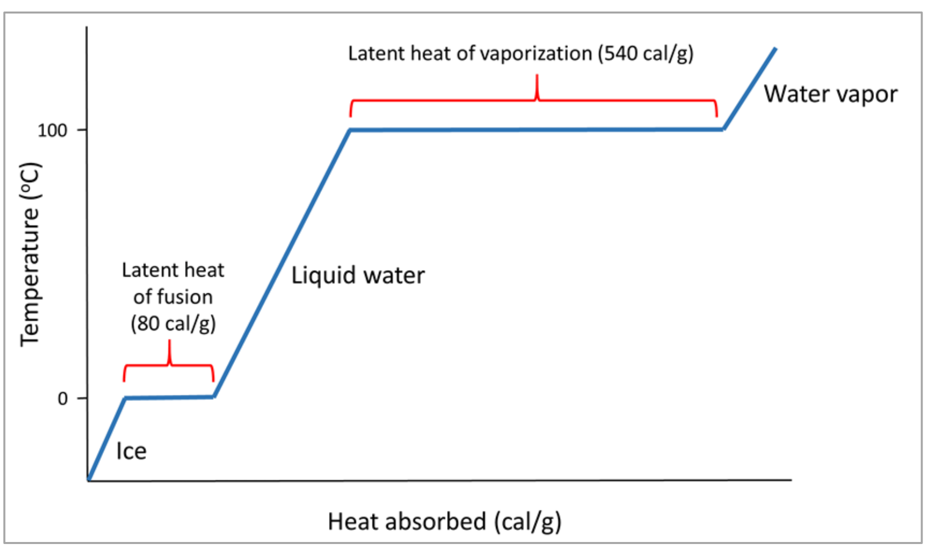

Figure 7.3. Latent heat required for phase changes in water. Latent heat of fusion is the heat required to melt ice and latent heat of vaporization is the heat required to turn liquid water into water vapor. **Source**

Due to its high heat capacity, warm blooded animals use water to disperse heat more evenly and maintain a constant temperature in their bodies: it acts in a similar manner to a car's cooling system, transporting heat from warm places to cool places, causing the body to maintain a more even temperature.

7.2.3 Heat of Vaporization

Water also has a high **heat of vaporization**, the amount of energy required to change one gram of a liquid substance to a gas. A considerable amount of heat energy (540 calories/g) is required to accomplish this change in water (**Figure 7.3**). This process occurs on the surface of water. As liquid water heats up, hydrogen bonding makes it difficult to separate individual liquid water molecules from each other, which is required for water to enter the gas phase (steam). Thus, water acts as a heat sink and requires much more heat to boil than liquids such as ethanol, whose hydrogen bonds are weaker. Eventually, as water reaches its boiling point of 100° Celsius (212° Fahrenheit), there is sufficient heat to break the hydrogen bonds, and the kinetic energy between the water molecules allows them to escape from the liquid as a gas: this process is known as **evaporation**. Even when below its boiling point, water's individual molecules acquire enough energy from other water molecules such that a few surface water molecules can escape and vaporize.

Since hydrogen bonds need to be broken for water to evaporate, a substantial amount of energy is used in the evaporation process. As the water evaporates, energy is transferred from one source and taken up by the process, cooling the environment where the evaporation is taking place. In many living organisms, including humans, the evaporation of sweat (which is 90 percent water) allows the organism to cool when significant heat energy is transferred from the organism to the water in the sweat, helping to maintain a constant body temperature, a process known as **homeostasis**.

7.2.4 Universal Solvent

Water is often referred to as a **universal solvent**, because it can dissolve more substances than any other common liquid. This remarkable ability arises from water's polarity; its slightly positive and negative ends allow it to interact with and dissolve other *polar* molecules and *ionic* compounds. When a substance (solute) enters water, the charged regions of water interact with the particles of the solute (opposite charges attracting each other) and help pull them apart. A familiar example is table salt (sodium chloride) which is shown in **Figure 7.4**. When salt is added to water, the negative ends of water molecules surround the positively charged sodium ions (Na^+), while the positive ends surround the negatively charged chloride ions (Cl^-). This process, called **dissociation**, breaks the ionic bonds holding the salt crystal together, causing it to dissolve and disperse evenly throughout the water. Because water can interact with and dissolve so many types of molecules (ionic compounds, many polar molecules, gases like oxygen and carbon dioxide) it plays an essential role in biological and environmental processes, from nutrient transport in cells to chemical reactions in soils and aquatic systems. This is very important as it enables water to dissolve various chemicals and distribute them within living organisms, including taking toxic substances out of living things, and in the environment.

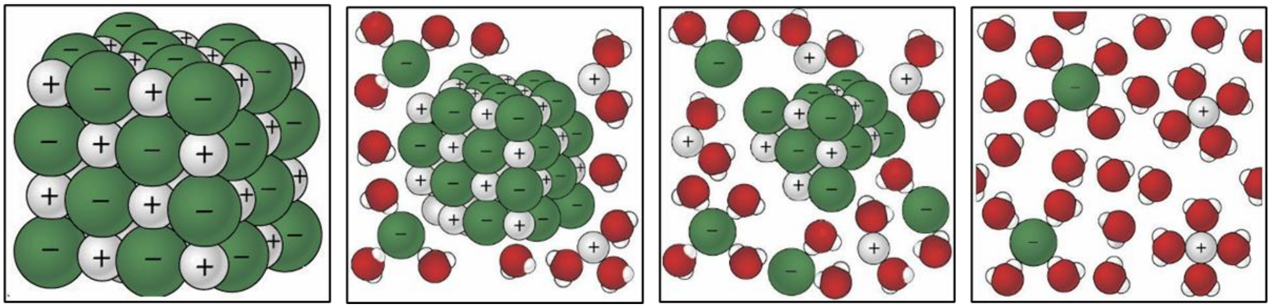

Figure 7.4. The first image starting from the left is of salt crystals (NaCl) held together by ionic bonds. Na^+ are the positively charged white particles and Cl^- are the green negatively charged ones. In the second image, water is added and begins to pull the ions apart due to the attraction between opposite charges. In the last image, you see Na^+ ions surrounded by the oxygen side of water molecules and Cl^- are surrounded by the hydrogen side (Source).

7.2.5 Cohesion, Surface Tension, and Adhesion

Have you ever filled a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass (**Figure 7.5**). This water can stay above the rim of the glass because of the property of water known as **cohesion**, that causes water molecules to "stick together." In cohesion, water molecules are attracted to other water molecules (because of hydrogen bonding), keeping the molecules together at the liquid-gas (water-air) interface allowing water molecules to protrude above the top surface of the glass. Cohesion creates surface tension, which is the "skin-like" surface that forms on water. **Surface tension** is described as the capacity of a substance to resist rupture when placed under tension or stress. This is also why water forms droplets when placed on a dry surface rather than being flattened out by gravity (**Figure 7.5**).

Cohesion and surface tension resulting from the hydrogen bonds between water molecules create a surface that supports the item on the top. Molecules at the surface are pulled tightly together by the cohesive forces from the water below them. This makes the surface behave like a stretched elastic film. Because of surface tension, small insects like water striders can "walk" on water, and objects such as paper clips or a needle can briefly float if placed gently on the surface as shown in **Figure 7.6**.

While cohesion is the attraction between water molecules, **adhesion** is the attraction between water molecules and other surfaces. Because water is polar, it can "stick" to many materials, such as the walls of plant vessels or thin tubes. This attraction is sometimes stronger than water's cohesive forces, especially when water is exposed to charged surfaces such as glass walls of capillary tubes (narrow glass tube). Adhesion is observed when water

Figure 7.5. Left: Water in a glass forms a dome shape above the glass due to cohesive forces of attraction among water molecules (credit: Sam Mutiti). Middle image: Beading up of water on a leaf surface (credit: Microsoft stock images). Right image: formation of droplets at the tip of pine needles due strong cohesive forces between water molecules (credit: J Schmidt; National Park Service).

"climbs" up the tube placed in a glass of water (**Figure 7.7a**): notice that the water appears to be higher on the sides of the tube than in the middle. When cohesion (water sticking to water) works together with adhesion (water sticking to another surface) (**Figure 7.7b**), the result is **capillary action**, which is the ability of water to move upward through narrow spaces without the help of external forces, and even against gravity.

Figure 7.6. The weights of the needle (left image), paper clip (middle), and water strider (right image) are pushing the surface downward; at the same time, the surface tension is pushing it up, suspending them on the surface of the water and keeping them from sinking. (Credit: Cory Zanker (left), Howard Perlman (middle) and Tim Vickers (right)

In plants, capillary action helps water rise through tiny vessels in the roots and stems. Adhesion causes water molecules to cling to the walls of the vessels, and cohesion pulls other water molecules along with them. This process helps move water from the soil all the way to the leaves, where it is used for photosynthesis and lost through transpiration (**Figure 7.7c**). In animals, including humans, adhesion also plays a role in how blood moves through very small blood vessels. In narrow capillaries, water in the blood adheres to the vessel walls, helping blood flow smoothly through these tiny tubes and allowing oxygen and nutrients to reach tissues.

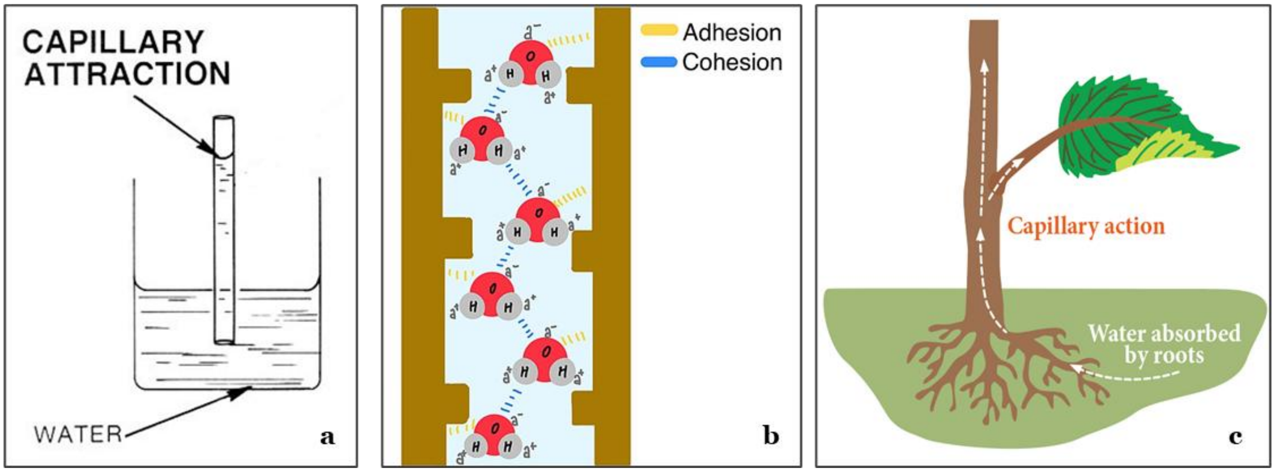

Figure 7.7. a) Capillary attraction in a glass tube allows water to move upwards against gravity (credit: Pearson Scott Foresman). **b**) a closer looks at how cohesion and adhesion are working together (credit: TiffanyChan0926 CC-BY-SA-4.0). **c**) showing how capillary action enables water movement through plants from the roots to the leaves (Source: Museum of natural and cultural history, UO)

Test your knowledge…

ALL BECAUSE OF WATER'S SPECIAL PROPERTIES

Some of the properties of water can be directly observed in everyday occurrences. Match each real-world example (1–10) with the correct water property (A–F). Some properties may be used more than once.

***Water Properties**:*

A) Cohesion and adhesion
B) High specific heat
C) Lower density of ice
D) Universal solvent
E) Surface tension
F) Evaporative cooling

Scenarios

1. ______ *Drinking through a straw*
2. ______ *Water beading up on a car hood after rain*
3. ______ *Ice floats in your drink*
4. ______ *Salt or sugar dissolving easily when making a drink*
5. ______ *A water strider walking across a pond surface*
6. ______ *Sweating helps cool your body on a hot day*
7. ______ *Fish survive under ice-covered lakes in winter*
8. ______ *Water moving upward in plant stems*
9. ______ *Oxygen dissolving in water so fish can breathe*
10. ______ *Ocean water takes longer to heat up and cool down compared to land*

7.3 Global Water Distribution and Use

Although Earth is often called the "water planet" since about 71% of the surface is covered by water, most of its water is not directly usable by humans (**Figure 7.8**). Approximately 97.5% of all water on Earth is saltwater (saline), most of which (96.5%) is found in oceans. The remaining 2.5% is freshwater, but even that is mostly inaccessible: roughly 68% of *freshwater* is locked away in icecaps and glaciers. Therefore, at least 99% of all water on Earth is generally unsuitable for human use because of salinity (ocean water) and location (ice caps and glaciers), leaving less than 1% of total water as fresh water that is available for consumption. Of this available fresh water, approximately 97% is groundwater, stored deep below the surface of the Earth, leaving a very small proportion of Earth's water (about 0.01%) available in rivers and lakes (surface water) where nearly all human water use occurs because it's easily accessible. Because only a tiny fraction of Earth's water is accessible for human use, understanding how this limited supply is distributed and used is essential for managing it responsibly. In the next sections, we'll briefly look at some examples of the major types of water use and the sectors that rely most heavily on freshwater resources.

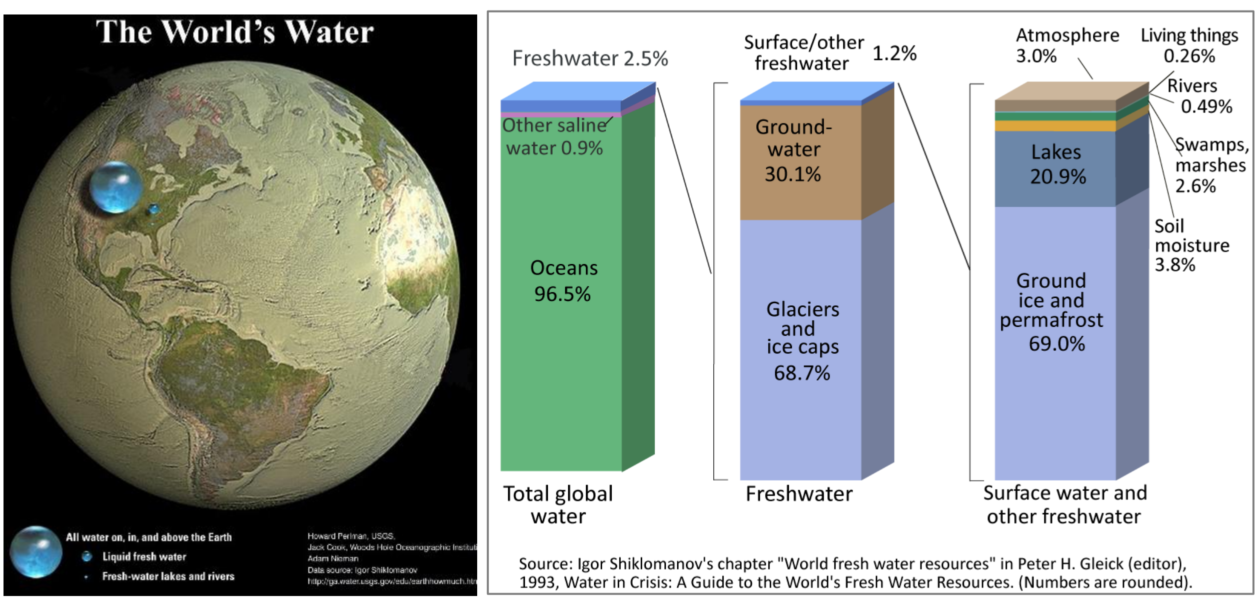

Figure 7.8. Graphical representation of the types and distributions of water. The globe on the left shows the relative "size" of accessible freshwater relative to all water on Earth. The three bars on the right show proportions - **left bar** is all water, freshwater and saline, on, in, and above the Earth; **center bar** is all freshwater; **right bar** is only the portion of freshwater residing in surface water (rivers and lakes, etc.), snow and ice, and relatively-shallow ground water. (Source: USGS)

7.3.1 Consumptive and Non-consumptive Use

There are three main sectors that use water – industrial, agricultural, and domestic. When water is removed from its source such as river or lake and returned to this source after use, this is referred to as **non-consumptive use**. An example is when water is used in industrial cooling, it may be temporarily placed in cooling ponds and later returned back to the river or lake that it came from. **Consumptive use** is when water is taken out from a source and consumed by plants and animals or used in industrial processes. The water enters animal tissue or becomes part of industrial products or evaporates during use and is not returned to its source. Of the three sectors, the agricultural sector is by far the largest user of water that is never returned to its sources, *consumptive use*.

7.3.2 United States' Use

The USGS has estimated water use for the United States every 5 years since 1950. Estimates are provided for groundwater and surface-water sources, for fresh and saline water quality, and by sector or category of use. National data show that agriculture accounts for the largest share of water withdrawals, followed by water used for thermoelectric power generation and then public supply for homes and businesses (**Figure 7.9**). These patterns vary by region, climate, and population density. To explore interactive maps and up-to-date data on how water is used in the United States and where it comes from, visit the ***USGSVizlab water data visualization*** website.

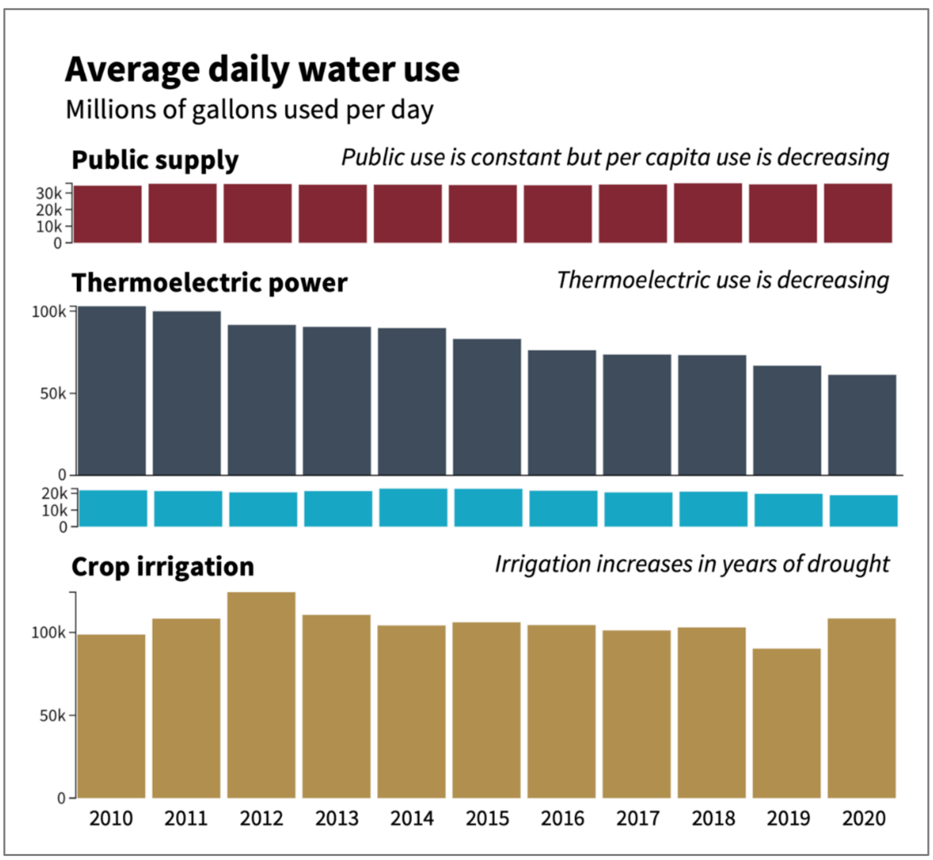

Figure 7.9. Estimated 2010 - 2020 water withdrawals in the US. Irrigation and thermoelectric power usages account for most water withdrawals (Source: USGS). More water use terminology can be found here.

7.3.3 Other Examples

In Europe, most water used comes from surface waters. Around 75% of total water abstraction is from rivers and reservoirs, and 25% from groundwater. Like the US, agriculture is the sector that uses the largest share of freshwater (58%), followed by energy cooling (18%), mining (11%) and households (10%). Australia's water supply in 2021–22 came overwhelmingly from surface water (95%) of all self-extracted water, while groundwater contributed roughly 5%, and desalinated seawater less than 1%. Households used about 15% of all distributed water, with industries using the remaining 85%. Agriculture was the largest user of distributed water, receiving about 61% of all water supplied to industries. In Egypt, irrigation accounts for over 70% of water withdrawn. Irrigation is water that is applied by a water system to sustain plant growth. Irrigation also includes water that is used for frost protection, application of chemicals, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching salts from the root zone. Water is being used at very high rates worldwide due to human population growth and industrialization. As more countries become affluent (increase in industrialization and standard of living) they consume more water than they did when they were less industrialized. To find out more about global water use checkout the world water use meter.

Test your knowledge…

WHY FRESHWATER IS SO RARE!

1. *The majority of the Earth's water is found in the ______ (name the type of water body).*
2. *The majority of Earth's freshwater is stored in ______ (name the form and location).*
3. *The majority of usable freshwater for human needs is in ______ (name the source).*
4. *When water is withdrawn for use and not returned to its original source, this is _____.*
5. *In both the U.S. and globally, the sector with the largest consumptive use of water is ______ (name the sector).*
6. *Why is public water supply staying constant even as population continues to increase?*
7. *With time, do you think the total amount of water on the planet increases, decreases, or stays the same? Explain your reasoning.*

7.4 The Hydrologic Cycle

The hydrologic cycle (water cycle) represents a continuous global cycling of water from one component to another (**Figure 7.10)**. This process is powered by two major forces - heat energy from the Sun that causes liquid water to change to water vapor and the gravitational pull of the Earth that brings water to the surface. This is a complex process involving *pools* and *fluxes*. **Pools** (also stores) are the many forms and places where water is stored (like a swimming "pool,"). The main pools include oceans, ice caps and glaciers, groundwater, the atmosphere, rivers, lakes, soil, and living organisms (plants and animals). Water spends different amounts of time in each pool depending on the volume of water and the rate at which water enters and leaves that pool. **Fluxes** refer to the ways that water moves between the pools, including state changes from solid to liquid to gas and back. The main fluxes include evaporation, sublimation, condensation, transpiration, precipitation, transportation, deposition, runoff, and infiltration.

To better appreciate how the water cycle works, let's follow a single water molecule as it moves through different pools. Imagine it begins in the ocean. When heated by the sun, the molecule may evaporate and enter the atmosphere. **Evaporation** is the process in which liquid water changes into water vapor. Evaporation is the main way water returns to the air; it contributes nearly 90% of atmospheric moisture, with most of the remaining 10% coming from **transpiration**, the evaporation of water from plant leaves. As plants pull water from the soil up to tiny pores on their leaves (stomata, plural is stoma), some of that water changes to vapor and exits into the air.

Together, evaporation from surfaces and transpiration from plants are known as **evapotranspiration**. Once water vapor enters the atmosphere, rising air currents carry it upward, where cooler temperatures cause it to condense into liquid droplets that form clouds. In the atmosphere, water can be **transported** over great distances in all three phases (gas, liquid, and solid) with moving clouds offering a visible example of this movement. **Condensation** refers to the change from vapor to liquid, while **deposition** occurs when water vapor turns directly into ice without first condensing. As clouds accumulate moisture and become saturated, they release water as **precipitation**, which reaches Earth as rain, snow, sleet, or hail. Snowfall may accumulate in glaciers or ice caps, storing water for long periods before it reenters the cycle. Water locked in ice can also return directly to vapor without melting through **sublimation**.

Did you know that the oldest known glacier ice is in the Allan Hills of Antarctica, estimated to be nearly 8 million years old?

Precipitation that falls as liquid usually ends up as **surface runoff** and **stream flow**. **Surface runoff** is the portion of precipitation that travels over the soil surface to the nearest stream channel. **Stream flow** is the movement of water in a natural channel, such as a river. Most precipitation falls directly onto the ocean and returns the water molecule back to restart the journey. This is also true for surface runoff, most of the water eventually returns to the ocean via stream flow. This also returns the water molecule back the ocean to start the journey again.

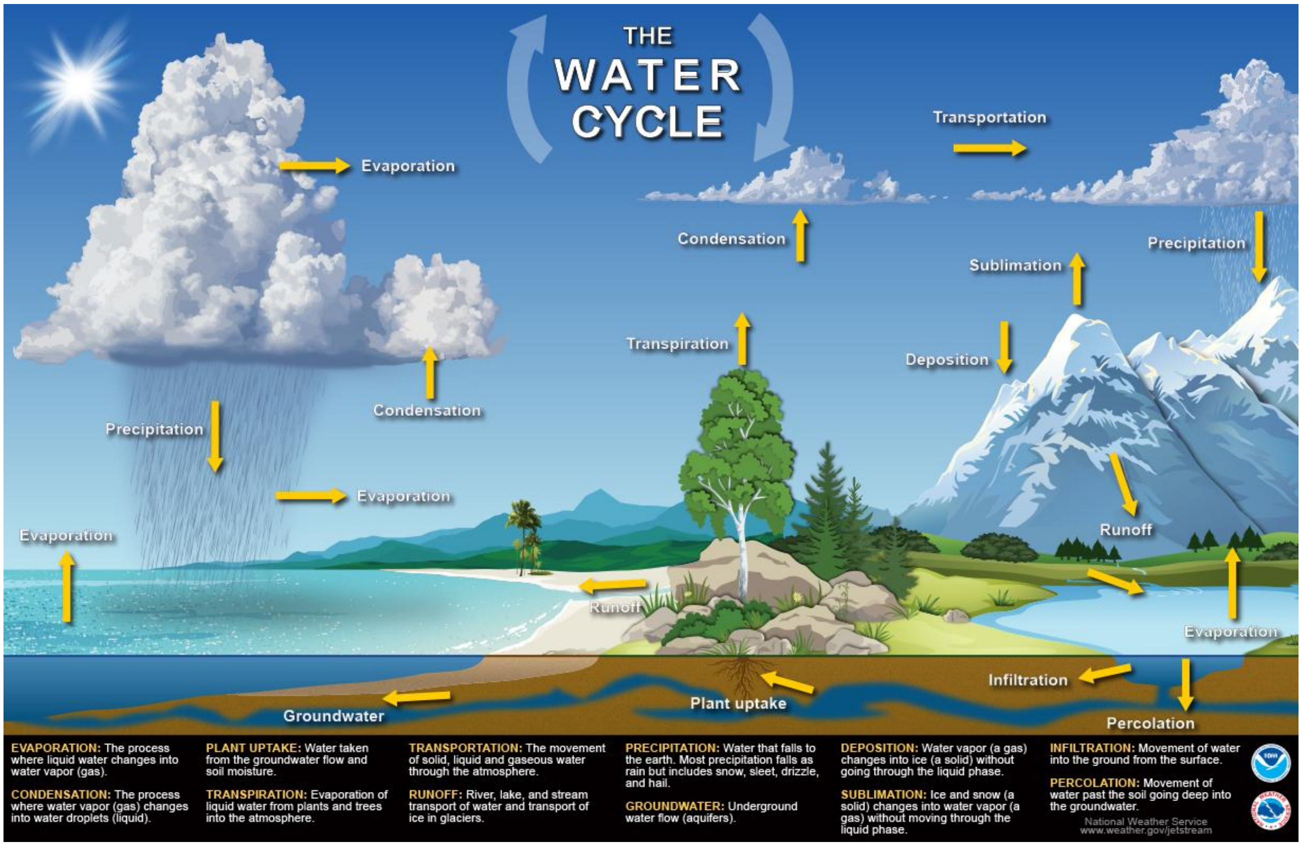

Figure 7.10. The water cycle at the global scale showing water moving through all the major pools, including the ocean (Source: NOAA). For a different water cycle that incorporates different types of human land use, see this USGS Water Cycle.

Water that falls as precipitation on lakes can evaporate back into the atmosphere and later return as precipitation. Aquatic plants in the lake can also take up water, which is then released through transpiration, returning it to the air. Some precipitation infiltrates the ground, a process in which water moves downward into the soil due to gravity (**infiltration**), becoming part of soil moisture and/or groundwater. Water that reaches deeper layers can recharge **aquifers**, which are saturated underground materials that store large amounts of freshwater for long periods. Some infiltrated water remains near the surface and gradually seeps back into rivers, lakes, or the ocean as **groundwater discharge**, and in some cases, groundwater emerges as freshwater **springs**. Water held in the soil near the surface can be absorbed by plant roots and later transpired from leaves. Over time, all of this water continues to move through the cycle, with most eventually returning to the ocean.

Test your knowledge…

THE ENDLESS CYCLE!

1. *The two forces that power the hydrologic cycle are _______.*
2. *This flux moves water from the atmosphere and delivers it to the Earth's surface _______.*
3. *Plants move water from the soil to the atmosphere through a process known as _________.*
4. *Water above the surface can be pulled below the surface by gravity and can replenish groundwater. This process is known as _____.*
5. *The process in which water vapor turns to liquid water to form clouds*
6. *Solid ice changing to water vapor is termed _________.*
7. *The flux that turns water from liquid to vapor is _____.*

7.5 Components of the Hydrologic Cycle

7.5.1 The Atmosphere

The atmosphere plays a vital role in the movement and transformation of water within the hydrologic cycle. It serves as the transport system that moves water between Earth's surface and other components of the cycle. Through **evaporation** and **transpiration**, water enters the atmosphere as *vapor*. Once there, it can be **transported** across vast distances, **condense** into clouds, and eventually return to the surface as **precipitation**. Although the atmosphere contains only a small fraction of Earth's total water, its influence is enormous because it determines where, when, and how much water falls back to the surface. In this way, the atmosphere links the oceans, land, and living organisms into a single, dynamic system that continuously redistributes water and energy around the planet.

Precipitation, the water released from clouds, can be in the form of rain, freezing rain, sleet, snow, or hail, although most precipitation falls in the form rain. There are three main kinds of rain; **frontal**, **convective**, and **orographic**. **Frontal** rainfall occurs when two air masses with different temperatures meet, forming a **front**. The warmer, lighter air is forced to rise over the cooler, denser air. As the warm air rises, it cools, and the water vapor in it condenses into clouds and precipitation. This process often produces steady, widespread rain and is common in regions where warm and cold air masses frequently collide. **Convective** rainfall is formed when intense localized heating causes hot moist air to rise and condense and form rain clouds. This type of rain is often intense but short-lived and is common in hot, tropical regions or during summer afternoons. **Orographic** rainfall is rain that forms over mountains. When a moist air mass encounters a mountain, it rises and cools. As it cools water vapor condenses to form rain clouds that produce rain on the windward side of the mountain. Most of the rain ends up as surface water runoff. **Surface water** is a major component of the hydrological cycle and one that we interact with very regularly. It includes lakes, wetlands, stormwater **runoff** (overland flow), ponds, potholes, rivers and streams, and the ocean.

7.5.2 Streams and Rivers

A river forms from water moving from higher to lower altitude (elevation), under the force of gravity. When rain falls on the land, it can infiltrate (seep) into the ground, become runoff (water running on the surface), or evaporate. Water that moves as runoff on the land surface usually converges as it moves towards lower elevation. The converging runoff can concentrate into single channels of conveyance called creeks, stream, or rivers. Usually these start as small **rills** and **rivulets** that would join up downhill into larger creeks, which then become streams, and later join up downstream to form even bigger channels referred to as rivers. The streams and small rivers that join up to form a larger river are called **tributaries, Figure 7.11**. The land area drained by a river and all its tributaries is called a **watershed** or catchment or river basin.

Figure 7.11: River systems. (left) A satellite image of a river system with multiple **tributaries**. (right) Two tributaries of the Zambezi River (one of Africa's major rivers) and their **watersheds** which cover Zambia, Zimbabwe, Angola, Namibia and Mozambique (Map created using Google Earth from Google Inc.)

Another feature associated with streams and rivers is the **floodplain,** which is the low-lying area adjacent to a river and is characterized by frequent flooding, a means by which rivers temporarily store excess water during storm events. The frequent flooding also delivers nutrient-rich sediments, making floodplains among the most fertile landscapes. Historically, this fertility attracted human settlement and agriculture (**Figure 7.12**). However, such land use often reduces the floodplain's ability to store water, increasing flood severity downstream. Impervious surfaces like roads and buildings further limit infiltration and water storage, contributing to more frequent and intense floods. While some agricultural practices, such as rice cultivation, are generally compatible with floodplain function, others can degrade these ecosystems. Properly functioning floodplains alleviate flood impacts by reducing peak flows, filter stormwater to protect water quality, and serve as important zones for groundwater recharge.

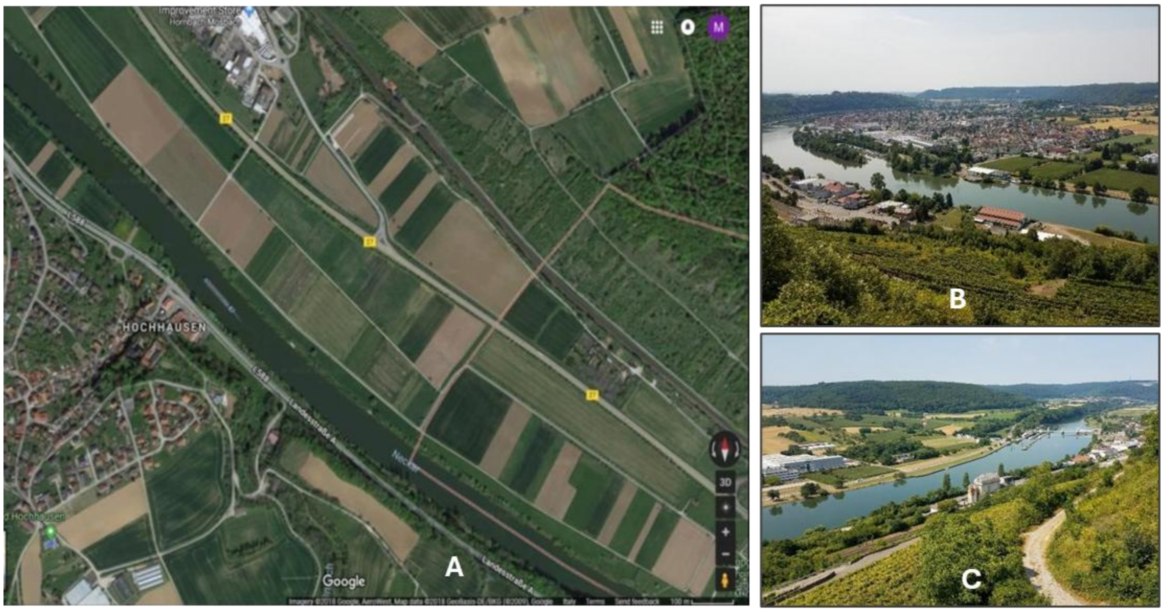

Figure 7.12: The Neckar River in Germany. A) Portion of the Neckar River where the flood plain is agricultural fields that allow the plain to function effectively. B and C) Meandering portion of the river with a mature flood plain showing substantial human development (buildings and agriculture) (Photo credit: Sam Mutiti). (Image credit: Google Inc.).

The United States of America (US) has numerous rivers that run throughout the nation's landscape. It is estimated that the US has over 200,000 rivers with the Mississippi River being the largest by volume despite it only being the second longest. The Missouri River is the longest river in US. Most States have at least one important river. In Georgia, the main rivers are the Flint, Ochlockonee, Suwannee, Saint Mary's, Satilla, Ogeechee, Altamaha, Oconee, Savannah, Chattahoochee, Tallapoosa, Coosa, Ocmulgee and the Tennessee rivers (**Figure 7.13**).

Rivers are important sources of water for cities and their populations. They also contain important biological communities and provide opportunities for recreational activities such as swimming, fishing, canoeing, and white-water rafting among others. Rivers largely control settlement patterns all over the world due to their widespread distribution and being an easily accessible source of water. Major cities, communities, factories, industries, and power stations are located along rivers. It is, therefore, very important to protect the quality and integrity of rivers all over the world.

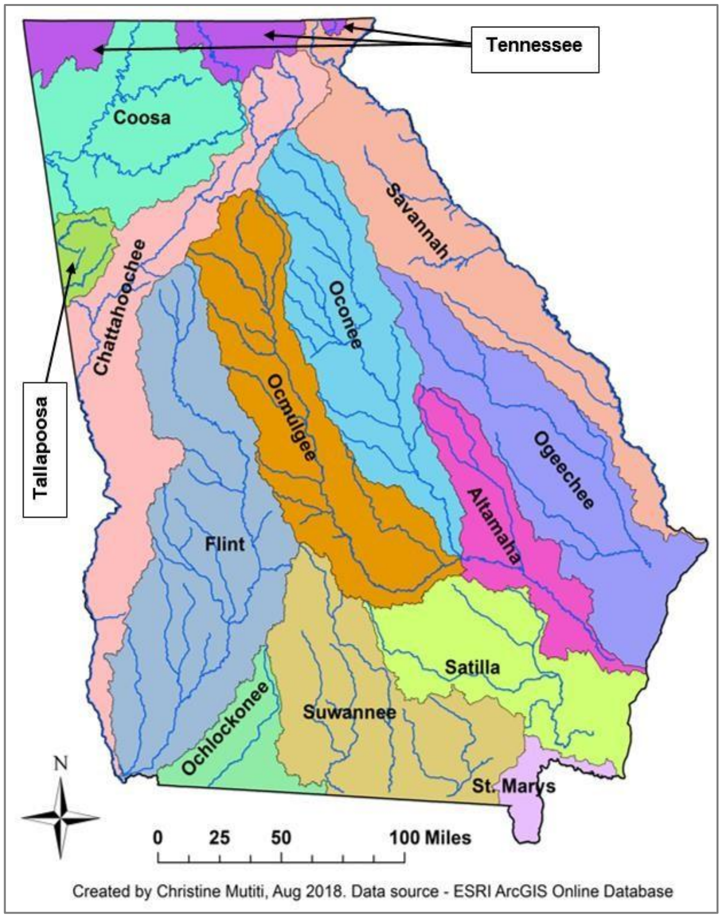

Figure 7.13: Watersheds (river basins) of Georgia, USA representing the main rivers in the state.

Did you know that some rivers flow underground through lava tubes or** karst (limestone) systems**, disappearing and reappearing miles away.

Unfortunately, many rivers in the world are too polluted to support some human activities, especially swimming, fishing, and drinking. For example, according to EPA data (2018-2019), about 30% of US river and stream miles exceed bacterial thresholds that could make them unsafe for recreational contact, and 44% show degraded biological communities. A lot of the rivers have also been dredged, channelized and restricted in width (**Figure 7.14** top images) or impounded by dams **(Figure 7.14** bottom images**)** which may impair their ability to support a lot of human and other biological activities.

The impoundments can trap stream sediments resulting in reduced sediment supply downstream, as well as increased deposition behind the dam. This shift in sediments flow can disrupt and damage aquatic habitats and can increase downstream stream erosion due to lack of sediment supply. The impoundments can also prevent certain aquatic organisms from migrating either upstream or downstream, therefore, reducing their range and ability to survive environmental changes as well cutting them off from spawning areas (e.g. salmon spawning). Construction of dams can also result in displacement of the local people and loss of traditional lands and cultural history to the reservoirs and ponds that usually form behind these impoundments.

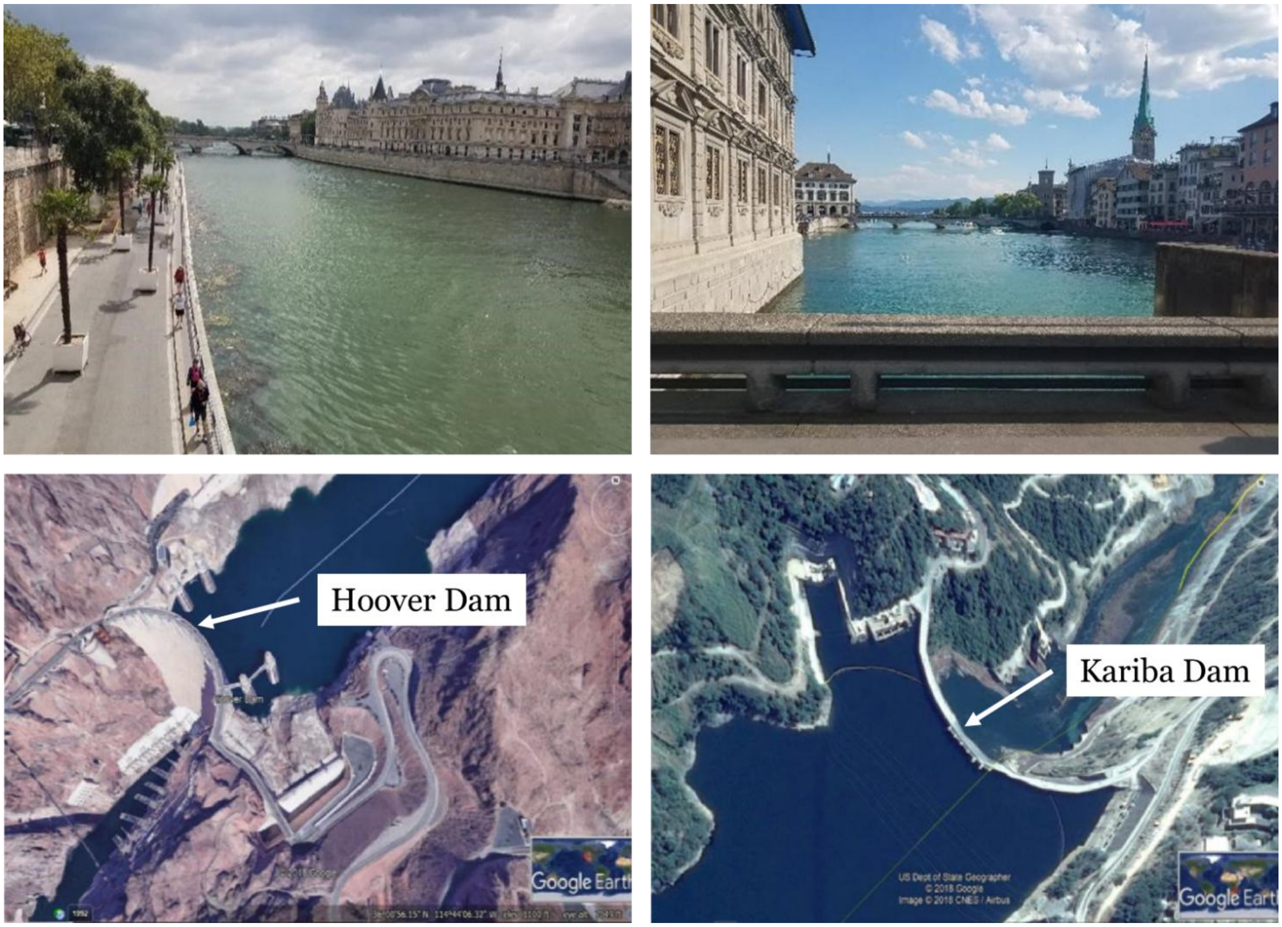

Figure 7.14: Channelized Rivers in Paris (City Center), France (top left) and Zurich (City Center) Switzerland (top right), (Photo credit: Sam Mutiti). Bottom images show two large dams used for hydroelectric power: (bottom left) Hoover Dam Between Nevada and Arizona in the eastern United States of America. (bottom right) Kariba Dam on the Zambezi River between Zambia and Zimbabwe). Image credit: (Google Earth)

It is estimated that over 600,000 river miles have been dammed in the US. Benefits of dams to humans include providing a source of water (reservoirs and farms ponds), recreation waters and controlling local flooding. On the flip side, dams can also have negative impacts on people and the environment. They can lead to increased severe flooding downstream of the dam, especially during high rain events or when they break. Some recent examples two dams that collapsed in Derna, Libya in September 2023, the Kakhovka Dam in Ukraine that collapsed in June 2023 and released thousands of toxic metals into the water, and the Orsk Dam in Russia that collapsed in April 2024 resulting in around 2000 evacuations.

7.5.3 Lakes, Reservoirs, and Ponds

If water flows to a place that is surrounded by higher land on all sides, a lake will form (**Figure 7.15**). A **lake** is a naturally occurring body of standing water, usually larger and deeper than a pond, where water collects in a basin surrounded by land. Lakes can be freshwater or, in some cases, salty, and they often support diverse ecosystems of plants, aquatic organisms such as fish, and other wildlife. A **pond** is a smaller, shallower body of standing water than a lake. Ponds also tend to have slower water movement and can warm up more quickly than lakes. A **reservoir** is a **man-made lake**, typically created by building a dam across a river or stream to store water for human use, such as drinking water, irrigation, or hydroelectric power. Like natural lakes, reservoirs can support aquatic life, but they are primarily managed for human purposes.

It is estimated that over 300 million water bodies in the world are lakes, reservoirs, and ponds. Most of the Earth's lakes (about 60%) are found in Canada. Even though lakes and rivers contain less than 1% of the Earths water, the US gets over two thirds (70%) of its water (for drinking, industry, irrigation, and hydroelectric power generation) from lakes and reservoirs. Lakes are also the cornerstone of the US's freshwater fishing industry and are the backbone of the nation's State tourism industries and inland water recreational activities.

Figure 7.15: Lake Sinclair in Baldwin and Putnam counties (Photo Credits: GCSU Hydro-Research lab)

7.5.4 Soil Moisture and Wetlands

Soil moisture refers to the water that is held in the spaces between soil particles. This water is essential for plant growth, influences how nutrients move through the soil, and affects the availability of water to ecosystems. Some areas of land are saturated (flooded) with water for at least part of the year during the growing season, creating conditions for **wetlands**. Wetlands are unique transitional zones between dry land and open water (rivers, lakes, ocean). They are identified using three characteristics: soils (water-saturated soils are present, also known as **hydric soils**), hydrology (shallow water table, hence flooding) and vegetation (wetland plants that are adapted to areas that are saturated with water for long periods of time, known as **hydrophytes**).These areas play a critical role in the water cycle by storing and slowly releasing water, filtering pollutants, and providing habitat for diverse species. Coastal wetlands act as natural buffers by absorbing wave energy and storm surges, helping to reduce the intensity of storms before they reach inland areas. Some major wetland types include **swamps** (dominated by trees), **marshes** (dominated by non-woody plants), and **bogs** (dominated by moss). Wetlands are very important areas of biological diversity and productivity. These are also important areas where geochemical and biological cycles/ processes are constantly taking place. For instance, wetlands are considered areas of significant carbon sequestration (storage), which impacts global climate change.

7.5.5 Oceans

Oceans are the largest component of the hydrologic cycle, storing about 97% of all water on Earth. The five oceans are the Atlantic, Indian, Pacific, Arctic, and Southern Oceans (**Figure 7.16**), and they receive water from most major rivers and dominate global water movement. Approximately 90% of the water that evaporates into the atmosphere comes from the ocean. Even though ocean water is salty, the water it contributes to the water cycle is *freshwater*, because only the water molecules evaporate; the salt and other dissolved minerals are left behind. Oceans are not only vast pools but also saltwater systems, with an average salinity of about 3.5%. This salinity affects the density of ocean water, drives circulation patterns, and shapes the types of organisms that can thrive there. Because oceans absorb and store enormous amounts of heat, they play a crucial role in regulating Earth's climate. Ocean currents move warm and cold water around the planet, helping to distribute heat and moderate temperatures across continents.

Did you know that the average depth of the oceans is about 3.6 km (about 2.2 miles) with a maximum depth that can exceed 10 kilometers (about 6.2 miles) in areas known as ocean trenches?

In addition to being central to climate and the water cycle, oceans support extraordinary biological diversity, from microscopic plankton to the largest animals on Earth. They also contain many unique landforms, such as mid-ocean ridges, trenches, and coral reefs. Despite their size, oceans face increasing threats from human activities, including pollution, overfishing, habitat destruction, and warming due to climate change.

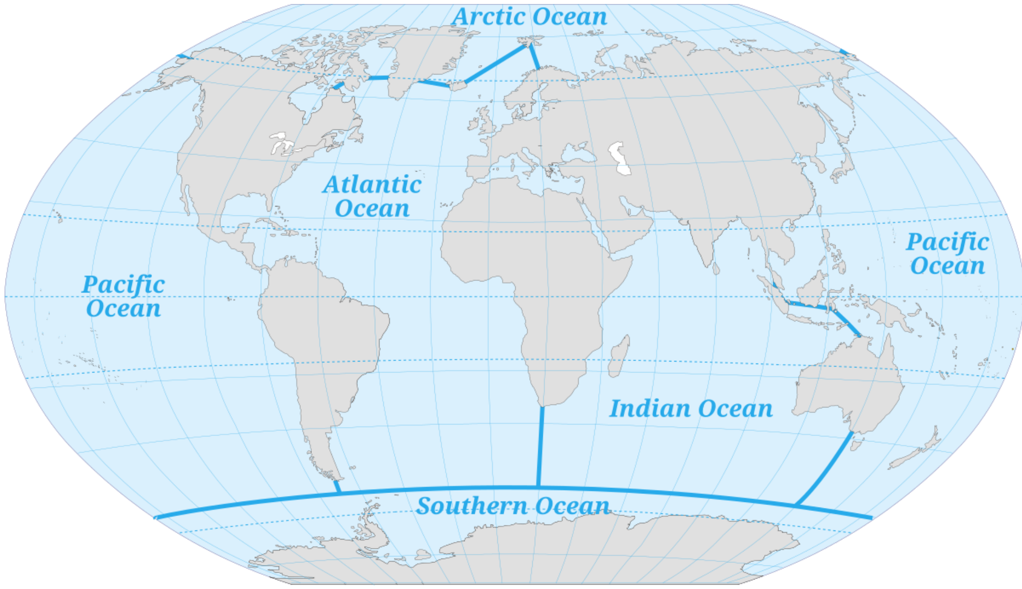

Figure 7.16: The five oceans found on planet Earth. The Pacific Ocean is the largest and deepest. Author: Pinpin, CC-BY-SA-3.0,2.5,2.0,1.0. To learn more, watch the video from the Habitable Planet: Oceans Video.

7.5.6 Groundwater

About 97% of the available freshwater on Earth is found below the surface as groundwater. Groundwater is not created by any mysterious process underground, it is simply part of the same recycled water that moves through the hydrologic cycle. When precipitation falls, some water flows across the land surface as runoff, while some enters the ground through **infiltration**. As water infiltrates, it moves downward through pores and spaces in soil, sediment, and rock. The upper layer it passes through is the **unsaturated zone** (**Figure 7.17**), where the spaces between particles contain both air and water. If the water continues to move downward, it eventually reaches the **saturated zone**, where all the pores and fractures are completely filled with water. This stored water is what we call **groundwater**. The top of the saturated zone is the **water table**, which marks the boundary between the saturated and unsaturated zones (**Figure 7.17**). Groundwater fills the cracks and spaces in underground materials much like water fills a sponge, and it can flow slowly through these spaces, supplying wells, springs, wetlands, and streams.

Large quantities of groundwater are stored in **aquifers**, which are underground rock formations or layers of sediment with enough pore space to hold large quantities of useable water and enough connectivity between the spaces to release the water. The ability of an aquifer to store and transmit water depends on two key properties: **porosity** and **permeability**. *Porosity* refers to the percentage of open space within a rock or sediment, while *permeability* describes how easily water can flow through those connected spaces. Groundwater exists only in the saturated zone, where all pores and fractures are completely filled with water. Water in the unsaturated zone above it is NOT considered groundwater;

instead, it is called **soil moisture** because the pores contain a mix of air and water (see **section 7.5.4**).

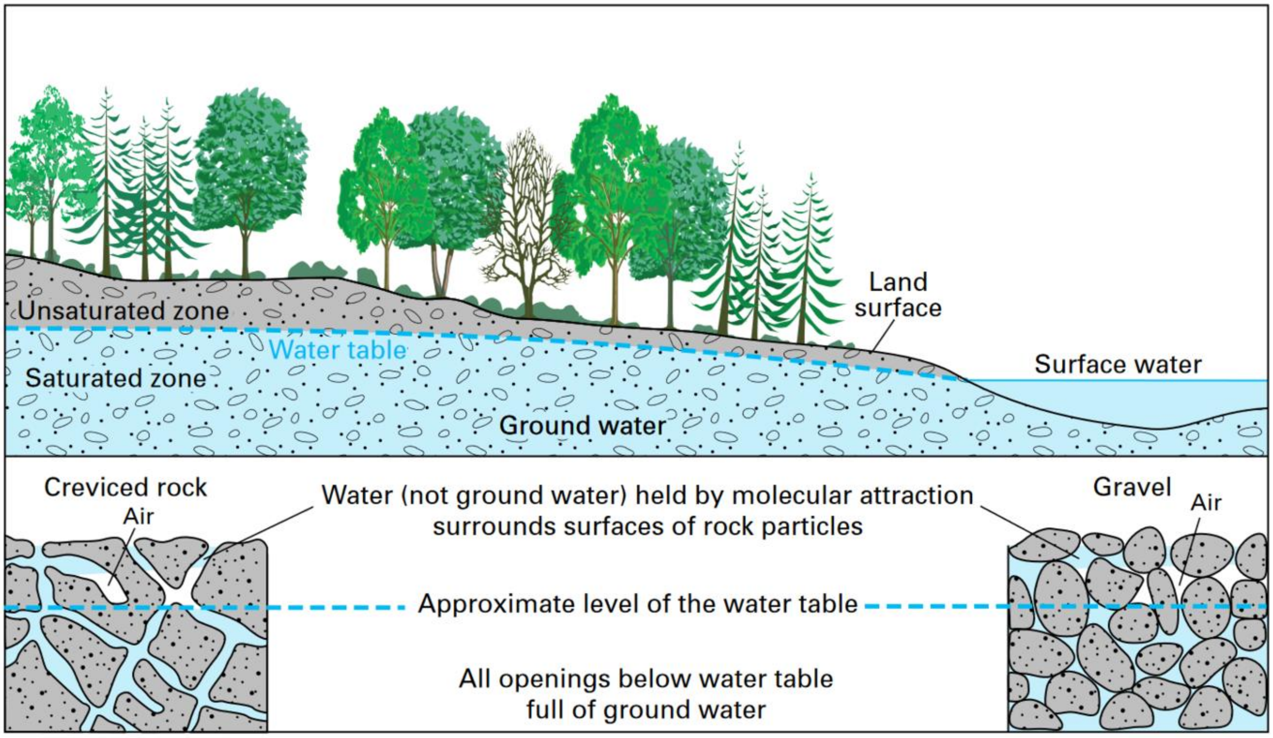

Figure 7.17: Model of groundwater system showing how groundwater occurs and the different terms associated with groundwater. Source: USGS

Unlike surface water, which always flows from higher to lower elevation, groundwater moves from areas of higher **hydraulic head** (higher energy) to areas of lower hydraulic head. This means groundwater may flow uphill or in unexpected directions depending on pressure, elevation, and subsurface conditions. Groundwater will continue to flow until it emerges as a spring, or discharges into surface water bodies on the land or in the ocean. Only a negligible amount of groundwater is stagnant at any given time in the subsurface. To utilize groundwater, we drill holes (wells) into the ground and pump the water out. While majority of the freshwater that is accessible for human use is located in groundwater, surface water (specifically rivers) are the most widely used sources of water both in the United States and around the world because they are easier to access and more widely distributed. Using groundwater requires special equipment to drill into the subsurface to extract the water and, aquifers are not as widely distributed as rivers.

Test your knowledge…

WHAT IS IT?

For each scenario below, determine what the component (pool) is based on the characteristics described.

1. *The only one that holds water in gaseous form.*
2. *The most widely distributed across land surface, delivering water from the highest points to the lowest.*
3. *Can be on land or the ocean and if its water went directly to the atmosphere, it would be called "sublimation"*
4. *The largest contributor of water to the water cycle*
5. *Water here often moves fast and we sometimes put up dams to generate electricity*
6. *These can be natural or manmade and water movement is slow*

7.6 Chapter Conclusion

Water is one of Earth's most essential substances, shaping weather, climate, ecosystems, and human societies. In this chapter, we explored water's unique chemical and physical properties, the processes of the hydrologic cycle, and the major pools that hold water across the planet and the fluxes that move the water between pools. From the cohesion that allows droplets to form, to the vast oceans that drive global climate, to the groundwater hidden beneath our feet, each part of Earth's water system plays a vital role in sustaining life.

Understanding how water behaves and moves is an important foundation for addressing the challenges we face today. As water flows through the environment, it interacts with rocks, soils, living organisms, and human activities. These interactions can introduce pollutants, alter natural processes, or reduce the availability of clean water for ecosystems and communities. At the same time, many regions around the world are experiencing **water scarcity**, where the demand for clean, accessible water exceeds the available supply. This scarcity is influenced by climate change, population growth, overuse of groundwater, and uneven distribution of freshwater resources. In the next chapter, we will explore this issue (scarcity) as well as **water quality**, including the factors that influence it, the major sources of contamination, and the strategies used to protect, conserve, and restore clean water. By connecting the science of water with the issues affecting it, we can better understand both the problems and the solutions needed to manage this critical and increasingly limited resource sustainably.

End of Chapter Review

1. How does the molecular structure of water lead to its unique physical and chemical properties?
2. What biological function/process in humans depends on water's high specific heat capacity and what would happen if say water had the same heat capacity as sand?
3. Discuss what would happen to planet Earth and its aquatic ecosystems if ice was denser than liquid water?
4. Choose two properties of water and explain how they work together to support life on Earth.
5. If water had a lower heat capacity and weaker hydrogen bonding, how might life on Earth be different?
6. Predict how the loss of water's solvent properties would affect a cell's ability to maintain homeostasis.
7. Where is majority of the Earth's freshwater located?
8. How does consumptive use of water differ from non-consumptive use?
9. Industrial cooling and agriculture are both heavy users of water. Explain how these two differ in the way that they use water.
10. The hydrologic cycle is driven by which two major forces?
11. Based on your understanding of what the hydrological cycle involves, which special property of water makes this process possible and why?
12. In the hydrologic cycle, what is the largest and most important pool?
13. Which pools in the hydrologic cycle are the most important sources of water for human use worldwide and why?
14. What is the difference between evaporation and transpiration?
15. What hydrologic cycle flux is responsible for replenishing groundwater?
16. Define groundwater and explain how it is different from soil moisture and surface water
17. What are the benefits and downsides of channelization and damming rivers?

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Terms

Adhesion
Aquifer
Bogs
Channelization
Cohesion
Condensation
Consumptive use
Convective rain
Covalent bond
Deposition
Dissociation
Evaporation
Evapotranspiration
Floodplain
Frontal rain
Groundwater
Groundwater discharge
Heat of vaporization
Hydric soils
Hydrogen bonding
Hydrophytes
Infiltration
Marshes
Non-consumptive use
Non-polar covalent bond
Orographic rain

Permeability
Polar covalent bond
Porosity
Precipitation
Rills
Rivulets
Saturated zone
Soil moisture
Specific heat capacity
Springs
Stream flow
Sublimation
Surface runoff
Surface tension
Swamps
Transpiration
Transportation
Tributaries
Unsaturated zone
Water table
Watershed
Wetlands