CHAPTER 8: WATER

Learning Objectives

As a result of this unit:

- Students will be able to draw multiple interacting water molecules and identify the bonds and atoms
- Students will explain how the molecular structure of the water molecule contributes to the unique properties of water.
- Students will demonstrate an understanding of how much water is available on Earth and how it is distributed
- Students will be able to compare regional and national responses to water issues.
- Students will be able to explain water-related problems (for example water scarcity, water-borne diseases, water pollution, flooding) from different regions of the world
- Students will be able to explain how human modifications of natural water systems can be both beneficial and destructive
- Students will be able to describe solutions to water-related problems
- Students will be able to read and interpret graphs and charts about water
- Students will demonstrate knowledge of some of the major regulations related to water in the USA
- Students will gain a rudimentary understanding of groundwater flow, management and protection
CHAPTER 8: WATER

This chapter has been adapted from OpenStax (Biology and Concepts in Biology texts), USGS Water Resources, the EPA and The Encyclopedia of Earth

“Whiskey is for drinking. Water is for fighting”

Introduction

Why do scientists spend time looking for water on other planets? Why is water so important? It is because water is essential to life as we know it. Water is one of the more abundant molecules and the one most critical to life on Earth. Approximately 60–70 percent of the human body is made up of water. Without it, life as we know it simply would not exist. The quotation above, which has been attributed to Mark Twain, suggests realism that water is extremely important. In recent years we have seen a rise in conflicts and dispute about water. Fortunately, most of the conflicts have ended up in the courts instead of the battlefields. This chapter is devoted to this precious resource that sustains our planet and its living things.

Chapter outline:

1. Properties of water
   a. hydrogen bonding
   b. Physical state of water
   c. Heat capacity
   d. Heat of Vaporization
   e. Universal Solvent
   f. Cohesion and Adhesion

2. Global Water Distribution and Use
3. The Hydrologic Cycle
4. Components of the Hydrologic Cycle
   a. Atmosphere and precipitation
   b. Rivers and Streams
   c. Lakes, Ponds and reservoirs
   d. Wetlands
   e. Oceans
   f. Groundwater
5. Water Scarcity and Shortage
6. Water Pollution and Quality
   a. Types of water pollution
   b. Sources of water pollution
7. Water Management
   a. Water pollution control
   b. Watershed Management
   c. Regulations

Water

Water is an important commodity for life on Earth and is something we all need in our daily activities. It has in human history been referred to as the “essence of life”, “blue gold” and “more precious than oil”. What makes water so important is its unique and special properties. These special properties of water include water’s high heat capacity and heat of vaporization, its ability
to dissolve polar molecules, its cohesive and adhesive properties, and its dissociation into ions that leads to the generation of pH. Understanding these characteristics helps to elucidate its importance in maintaining life on Earth. Before we discuss these properties we will review the molecular structure of water which gives rise to these special properties.

Properties of Water

A water molecule is composed of one oxygen and two hydrogen atoms that are joined together by polar covalent bonds. Covalent mean that the atoms share electrons, instead of completely giving up electrons to one another. Polar means that the electrons are not shared equally, the oxygen atom holds onto the electrons more strongly than the hydrogen atoms. These polar covalent bonds (figure 8.1), along with the molecular shape, cause a water molecule to be polar molecule, meaning that there is an uneven distribution of the charges. While there is no net charge to a water molecule, the polarity of water creates a slightly positive charge on hydrogen and a slightly negative charge on oxygen, contributing to water’s properties of attraction. Water’s charges are generated because oxygen is more electronegative than hydrogen, making it more likely that a shared electron would be found near the oxygen nucleus than the hydrogen nucleus, thus generating the partial negative charge near the oxygen.

<table>
<thead>
<tr>
<th>Bond type</th>
<th>Molecular shape</th>
<th>Molecular type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td><img src="https://example.com/water.png" alt="Water molecule" /></td>
<td>Polar</td>
</tr>
<tr>
<td>Methane</td>
<td><img src="https://example.com/methane.png" alt="Methane molecule" /></td>
<td>Nonpolar</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td><img src="https://example.com/carbon_dioxide.png" alt="Carbon dioxide molecule" /></td>
<td>Nonpolar</td>
</tr>
</tbody>
</table>

**Figure 8.1**: Whether a molecule is polar or nonpolar depends on both bond type and molecular shape. Both water and carbon dioxide have polar covalent bonds, but carbon dioxide is linear, so the partial charges on the molecule cancel each other out. Methane is also a nonpolar molecule (From OpenStax Concepts of Biology text)

Hydrogen Bonds

As a result of water’s polarity, each water molecule attracts other water molecules because of the opposite charges between water molecules. Because the hydrogen atom is slightly positive, it will be attracted to neighboring negative charges. When this happens, a weak interaction occurs between the positive hydrogen from one molecule and the negative charge on
the more electronegative atoms of another molecule, usually oxygen or nitrogen. This interaction is called a **hydrogen bond**. This type of bond is common and occurs regularly between water molecules. Individual hydrogen bonds are weak and easily broken; however, they occur in very large numbers in water and in organic polymers, creating a major force in combination. These hydrogen bonds contribute to the following water’s unique properties.

1. Water is the universal solvent
2. Exists in nature as a solid, liquid, and gas
3. The density of ice is less than liquid water
4. Water has a high surface tension
5. Water has a high heat capacity
6. Water exists as a liquid at room temperature

**Physical State of Water on Earth**

Water on Earth can naturally exist as solid, liquid or gas. The unique location in the Solar System, the tilt, rotation and revolution of our planet combine to make water present on all three states of matter. This has an important implication for life on Earth. The formation of hydrogen bonds is an important quality of liquid water that is crucial to life as we know it. As water molecules make hydrogen bonds with each other, it takes on some unique chemical characteristics compared to other liquids and, since living things have a high water content, understanding these chemical features is key to understanding life. In liquid water, hydrogen bonds are constantly formed and broken as the water molecules slide past each other. The breaking of these bonds is caused by the motion (kinetic energy) of water molecules due to the heat contained in the system. When the heat is raised as water is boiled, the higher kinetic energy of the water molecules causes the hydrogen bonds to break completely and allows water molecules to escape into the air as gas (steam or water vapor). On the other hand, when the temperature of water is reduced and water freezes, the water molecules form a crystalline structure maintained by hydrogen bonding (there is not enough energy to break the hydrogen bonds). The open structure of ice (Figure 8.2) makes ice less dense than liquid water, a phenomenon not seen in the solidification of other liquids.

Water’s lower density in its solid form is due to the way hydrogen bonds are oriented as it freezes: the water molecules are pushed farther apart compared to liquid water. With most other liquids, solidification when the temperature drops includes the lowering of kinetic energy between molecules, allowing them to pack even more tightly than in liquid form and giving the solid a greater density than the liquid.

The lower density of ice, illustrated in Figure 8.2, an anomaly, causes it to float at the surface of liquid water, such as in an iceberg or the ice cubes in a glass of ice water. In lakes and ponds, ice will form on the surface of the water creating an insulating barrier that protects the animals and plant life in the pond from freezing. Without this layer of insulating ice, plants and animals living in the pond would freeze in the solid block of ice and could not survive. The ice crystals that form upon freezing rupture the delicate membranes essential for the function of living cells, irreversibly damaging them.
Figure 8.2: Hydrogen bonding makes ice less dense than liquid water. (A) The lattice structure water is more condensed than that of ice (B & C). The lattice structure of ice makes it less dense than the freely flowing molecules of liquid water, enabling it to float on water. (Credit a: modification of work by Jane Whitney, image created using Visual Molecular Dynamics (VMD) software

High Heat Capacity

Water has the highest specific heat capacity of any liquid. Water’s high heat capacity is a property caused by hydrogen bonding among the water molecules. 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. For water, this amount is one calorie. It takes water a long time to heat up and a long time to cool. In fact, the specific heat capacity of water is about five times more than that of sand. This explains why land cools faster than the sea. Due to its high heat capacity, water is used by warm blooded animals to more evenly disperse heat and maintain 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.

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 (586 cal) is required to accomplish this change in water. This process occurs on the surface of water. As liquid water heats up, hydrogen bonding makes it difficult to separate the liquid water molecules from each other, which is required for it to enter the gaseous phase (steam). As a result, water acts as a heat sink or heat reservoir and requires much more heat to boil than does a liquid such as ethanol (grain alcohol), whose hydrogen bonding is weaker than water’s hydrogen bonding. Eventually, as water reaches its boiling point of 100° Celsius (212° Fahrenheit), the heat is able to break the hydrogen bonds between the water molecules, and the kinetic energy (motion) between the water molecules allows them to escape from the liquid as a gas. Even when below its boiling point, water’s individual molecules acquire enough energy from other water molecules such that some surface water molecules can escape and vaporize: this process is known as evaporation.

Since hydrogen bonds need to be broken for water to evaporate means that a substantial amount of energy is used in the evaporation process. As the water evaporates, energy is taken up by the process, cooling the environment where the evaporation is taking place. In many living
organisms, including in humans, the evaporation of sweat, which is 90 percent water, allows the organism to cool so that homeostasis of body temperature can be maintained.

Water as a Solvent

Since water is a polar molecule with slightly positive and slightly negative charges, ions and polar molecules can readily dissolve in it. Water is, therefore, referred to as a solvent, a substance capable of dissolving other polar molecules and ionic compounds. The charges associated with these molecules will form hydrogen bonds with water, surrounding the particle with water molecules. This is referred to as a sphere of hydration, or a hydration shell, as illustrated in Figure 8.3 and serves to keep the particles separated or dispersed in the water. When ionic compounds are added to water, the individual ions react with the polar regions of the water molecules and their ionic bonds are disrupted in the process of dissociation. Dissociation occurs when atoms or groups of atoms break off from molecules and form ions. Consider table salt (NaCl, or sodium chloride): when NaCl crystals are added to water, the molecules of NaCl dissociate into Na\(^+\) and Cl\(^-\) ions, and spheres of hydration form around the ions, illustrated in Figure 8.3.

![Figure 8.3](image)

**Figure 8.3** When table salt (NaCl) is mixed in water, spheres of hydration are formed around the ions. (After OpenStax Concepts of Biology text book)

When salt is mixed with water, the salt dissolves because the covalent bonds of water are stronger than the ionic bonds in the salt molecules. The positively-charged sides of the water molecules are attracted to the negatively-charged chloride ions and the negatively-charged sides of the water molecules are attracted to the positively-charged sodium ions. Essentially, a tug-of-war ensues with the water molecules winning the match. Water molecules pull the sodium and chloride ions apart, breaking the ionic bond that held them together. After the salt compounds are pulled apart, the sodium and chloride atoms are surrounded by water molecules, as this diagram shows. Once this happens, the salt is dissolved, resulting in a homogeneous solution.

Water's Cohesive and Adhesive Properties

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 8.4)
Figure 8.4. Water in a glass form a dome shape above the glass due to cohesive forces of attraction among water molecules. Photo Credit: Sam Mutiti

This water can stay above the glass because of the property of **cohesion**. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-gas (water-air) interface, although there is no more room in the glass. Cohesion allows for the development of **surface tension**, the capacity of a substance to withstand being ruptured 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 (Fig 8.5).

Figure 8.5. Beading up of water due strong cohesive forces between water molecules (Water USGS, right hand photo credit: J Schmidt; National Park Service).

When a small scrap of paper is placed onto the droplet of water, the paper floats on top of the water droplet even though paper is denser (heavier) than the water. Cohesion and surface tension keep the hydrogen bonds of water molecules intact and support the item floating on the top. It’s even possible to “float” a needle or an insect on top of a glass of water if it is placed gently without breaking the surface tension, as shown in Figure 8.6.
Another important property of water is **adhesion**, or the attraction between water molecules and other molecules. This attraction is sometimes stronger than water’s cohesive forces, especially when water is exposed to charged surfaces such as on the inside of thin glass tubes known as capillary tubes. Adhesion is observed when water “climbs” up the tube placed in a glass of water: notice that the water appears to be higher on the sides of the tube than in the middle. This is because the water molecules are attracted to the charged glass walls of the capillary tube more than they are to each other and, therefore, adhere to it. This type of adhesion is called **capillary action**, and is illustrated in **Figure 8.7**.
Global Water Distribution and Use

Most of the water on the planet is in oceans and unavailable for human consumption due to its high salinity (Figure 8.8).

![Distribution of Earth’s Water](http://water.usgs.gov/edu/earthwherewater.html)

Of all the water in the world, only about 0.64% is fresh water that is available for consumption (the other fresh water is locked up in ice). Of this available fresh water, 98.4% is found as groundwater below the surface of the Earth and only 1.4% is surface water in rivers and lakes. You can see in Table 8.1 and Figure 8.8 that groundwater is the largest available fresh water resource on Earth and, therefore, it is important to fully understand and protect this resource.

Table 8.1: Over a third of Earth’s fresh water is locked up in icecaps and glaciers leaving under a third available for human use.

<table>
<thead>
<tr>
<th>Sizes of Major Reservoirs</th>
<th>Sizes of Major Reservoirs</th>
<th>Sizes of Major Reservoirs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out of 35,000,000 km³ fresh water</td>
<td>Out of 1,386,000,000 km³ all water</td>
<td>Out of 10,600,000 km³ unfrozen fresh water</td>
</tr>
<tr>
<td>Reservoir</td>
<td>% of Total</td>
<td>Reservoir</td>
</tr>
<tr>
<td>Icecaps and Glaciers</td>
<td>69.6</td>
<td>Oceans and other saline</td>
</tr>
<tr>
<td>Fresh groundwater</td>
<td>30.0</td>
<td>Icecaps and Glaciers</td>
</tr>
<tr>
<td>Fresh surface water</td>
<td>0.299</td>
<td>Fresh groundwater</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>0.0368</td>
<td>Fresh surface water</td>
</tr>
</tbody>
</table>

Most of the water used by humans is surface water because of the ease of access and cheaper extraction (Figure 8.9). In the United States, about 40% of all public supplies and domestic water used is from groundwater. In some communities 100% of the domestic water is from groundwater. Public supply is water withdrawn by public and private water suppliers to
supply water for at least 25 people or have a minimum of 15 connections. **Domestic** water supplies is defined by the USGS as water that is used for indoor and outdoor uses at residences, and includes uses such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, watering lawns and gardens, and maintaining pools. As more pressure is placed on surface water by the ever increasing population and pollution from human activities, groundwater is becoming more and more important as a source of drinking water in the US (Figure 8.9 and 8.10) and the rest of the world.

Most of the water withdrawn from both surface and groundwater sources is mainly used for industrial cooling, irrigation and public water supply.

![Figure 8.9: Amount of water withdrawn from surface water sources compared to groundwater.](http://water.usgs.gov/edu/wusw.html)

**Fig. 8.9:** Amount of water withdrawn from surface water sources compared to groundwater. Most of the water withdrawn is from surface water sources

![Figure 8.10: Water withdrawals by usage. Most of the water withdrawn for thermoelectric power is surface water while most of the water withdrawn for domestic and mining use is groundwater.](http://water.usgs.gov/edu/wusw.html)

**Figure 8.10:** Water withdrawals by usage. Most of the water withdrawn for thermoelectric power is surface water while most of the water withdrawn for domestic and mining use is groundwater. http://water.usgs.gov/edu/wusw.html

Water usage can also be categorized as either **consumptive** or non-**consumptive** use. **Consumptive** use is that part of water withdrawn that is either evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate aquatic environment and not returned back. **Non-consumptive** use is the water that is withdrawn and returned back to the immediate environment with minimum loss. The largest percentage of water withdrawn goes to thermoelectric cooling, which is a non-consumptive use as it is returned to the same source (Figure 8.11). However, irrigation, water
that is applied by a water system to sustain plant growth, accounts for the most consumptive use of all water withdrawn. In some countries, such as 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.

![2010 withdrawals by category, in million gallons per day](http://water.usgs.gov/watuse/images/category-pages/2010/total-category-pie-2010.png)

**Figure 8.11:** Estimated 2010 water withdrawals. Irrigation and thermoelectric power usages account for most water withdrawals. http://water.usgs.gov/watuse/images/category-pages/2010/total-category-pie-2010.png

More water use terminology can be found at: [http://water.usgs.gov/watuse/wuglossary.html](http://water.usgs.gov/watuse/wuglossary.html)

In the US there is a difference in how states withdraw and use water (Figure 8.12). California and Texas account for over 20% of all water withdrawn. In fact, California consumes more water than is available within the state and is therefore forced to get water from the other states. Despite this deficiency almost everyone in California has access to clean and safe drinking water. Contrast this to Lusaka, the capital city of Zambia, which has more water available than is withdrawn but more than a third of its population has no access to safe drinking water. Can you think of a reason why not everyone in Lusaka has access to clean and safe drinking water?
Figure 8.12: A comparison of water usage by state, California and Texas use the most water in the United States. Data expressed as a percentage of the total water use in the US. (Source USGS)

The Hydrologic Cycle
The hydrologic cycle (water cycle) represents a continuous global cycling of water from one reservoir to another. This cycle can be viewed or represented at both the local (watershed) and global scales, Figures 8.13 and 8.14 respectively.

Figures 8.13: The water cycle representing how water moves on earth. The hydrologic cycle at the watershed scales, ocean reservoir not included.

The major water reservoirs on Earth are oceans, glaciers, groundwater, rivers and lakes. Water spends different amounts of time in the various reservoirs. The main factors that control residence time in a reservoir are size (volume of reservoir) and flux (rate of movement of water in and out of the reservoir).
To gain a deeper appreciation of the water cycle, let us follow a water molecule through the water cycle. Starting in the ocean (an arbitrary starting point) the water molecule can become part of the water that is converted into vapor and enter the atmosphere. Heat energy from the sun, which drives the water cycle, heats water in the oceans and cause evaporation. Evaporation is the process by which water changes from a liquid to a gas or vapor. Evaporation is the primary pathway that water moves from the liquid state back into the water cycle as atmospheric water vapor. Nearly 90% of moisture in the atmosphere comes from evaporation, with the remaining 10% is from plant transpiration. Transpiration is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapor and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves. Rising air currents take the vapor up into the atmosphere, along with water from evapotranspiration, which is a combination of water transpired from plants and that evaporated from the soil. The vapor rises into the air where cooler temperatures cause it to condense into clouds. Condensation is the process by which water vapor is converted from gaseous state back into liquid state. Clouds might eventually grow bigger and moist enough to release the water molecule in the form of precipitation. Precipitation is water falling from the clouds in the atmosphere in form of ice (snow, sleet, hail) or liquid (e.g. rain, drizzle). Precipitation that falls as snow can accumulate as ice caps and glaciers. Did you know that the largest glacier on Earth is the Severny Island ice cap in the Russian Arctic? These can melt and flow on land as overland flow. Precipitation that falls as liquid usually ends up as surface runoff in the form of overland flow and stream flow. Surface runoff is precipitation which 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. A majority of the 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 to the ocean to start the journey again.

A portion of the water that falls as precipitation can enter lakes where it can evaporate back into the atmosphere, condense and fall back as precipitation again. Water in the lake can also be taken up by plants and transpired back into the atmosphere. Some of the water that falls as precipitation can infiltrate into the ground and become part of groundwater. **Infiltration** is the process by which water enters the subsurface by gravitation pull. Some of the water infiltrates into the ground and replenishes **aquifers** (saturated subsurface rock), which store huge amounts of freshwater for long periods of time. Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as **groundwater discharge**, and some groundwater finds openings in the land surface and emerges as freshwater **springs**. Yet more groundwater is absorbed by plant roots to end up as evapotranspiration from the leaves. Over time, though, all of this water keeps moving and most of it ends up in the ocean.

**Components of the Hydrologic Cycle**

**Atmosphere and Precipitation**

Most precipitation falls in the form of rain. There are three main kinds of rain: **frontal, convective and orographic** (*Figure 8.15*). **Frontal** rainfall is precipitation formed when two air masses of different temperatures and moisture content converge. **Convective** rainfall is formed when intense localized heating causes hot moist air to raise, condense and form rain clouds. Intense rain would then fall as the clouds get supersaturated. **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 a rain cloud that produces rain on the windward side of the mountain (*Figure 8.15*). 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), water in ponds, potholes, rivers and streams.

**Streams and Rivers**

A river forms from water moving from a higher altitude to lower altitude, under the force of gravity. When rain falls on the land, it either evaporates, seeps into the ground or becomes runoff (water running on the surface). When water runs on the land surface it 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 rill and rivulets that would join up downhill into larger streams and creeks which can also join up downstream to form even bigger rivers. The streams and rivers that join up to form a larger river are called **tributaries**, *Figure 8.16*. The land area drained by a river and all its tributaries is called a **watershed** or catchment or river basin.
The area adjacent to a river that floods frequently is called a floodplain. **Floodplains** are areas that rivers use to temporarily store excess water during storm events and frequently contain very fertile soils. This has historically encouraged humans to move into floodplains and use them for agriculture, resulting in a reduction in the capacity of the floodplain to act as temporally storage for excess water during storm events, causing increased damaging flooding downstream. Properly functioning floodplains reduce the negative impacts of floods (by reducing severity of flood), and they assist in filtering stormwater and protecting the water quality of rivers. They also act as areas of recharge for groundwater.

**Figure 8.15**: Three main kinds of precipitation responsible for rainfall on earth *(Manning, 1996)*
The 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 Marys, Satilla, Ogeechee, Altamaha, Oconee, Savannah, Chattahoochee, Tallapoosa, Coosa, Ocmulgee and the Tennessee rivers (Figure 8.17).
These rivers are very important for supplying water to the cities and population of the states. The rivers also contain important biological communities and provide opportunities for recreation such as swimming, fishing and white water rafting. Rivers are so important in that, to a large extent, control settlement patterns all over the world. 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.

Unfortunately, most of the rivers in the world are too polluted to support certain human activities, especially swimming, fishing and drinking. Close to half of the rivers in the US have been deemed too polluted to support swimming and fishing. A lot of the rivers have also been channelized, dredged or impounded by dams which have ruined their ability to support a lot of human and biological activities. 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 reducing 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. 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 abilities to survive environmental changes as well cutting them off from spawning areas. Construction of dams can also result in displacement of the local people and loss of traditional lands and cultural history. Reservoirs and ponds usually form behind these impoundments.

**Lakes, Reservoirs and ponds:** If water flows to a place that is surrounded by higher land on all sides, a lake will form (**Figure 8.18**). A lake, pond or reservoir is a body of standing water on the land surface. When people build dams to stop rivers from flowing, the lakes that form are called reservoirs. 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 Earth’s 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. ([http://water.epa.gov/type/lakes/](http://water.epa.gov/type/lakes/))

**Figure 8.18:** Lake Sinclair in Baldwin and Putnam counties (Photo Credits: GCSU Hydrology Research lab)

**Wetland:** A wetland is an area which is home to standing water for notable parts of the year, has saturated soils for a large part of the year and has plants that require large amounts of water to survive. Wetlands include swamps, marshes, and bogs. Wetlands are identified using three characteristics: soils (water-saturated soils are present), hydrology (shallow water table) and vegetation (wetland plants that are adapted to areas that are saturated with water for long periods of time). Wetlands are very important areas of biological diversity and productivity. These are also important areas where geochemical and biological cycles/processes are consistently taking place. For instance wetlands are considered as areas of significant carbon sequestration (storage), which impacts global climate change. They also act as filters for storm-water runoff before it enters rivers and lakes.
Oceans

As you have probably already guessed, oceans are an important component of the hydrologic cycle because they store majority of all water on Earth (about 95%). Most of the major rivers drain into them. The five oceans covering the surface of the Earth are the Atlantic, Indian, Pacific, Arctic and the Southern Ocean (Figure 8.19).

Figure 8.19: The five oceans found on planet Earth. The Pacific Ocean is the largest. Source: http://theworldsoceans.com/

Approximately 90% of the water that is evaporated into the hydrologic cycle comes from the ocean. Oceans are an important and large part of the hydrologic cycle, with lots biological diversity and many landforms. Did you know that the average depth of the oceans is about 3.6 km with a maximum depth that can exceed 10 kilometers in areas known as ocean trenches? Ocean water is not available as freshwater because it is saline (saltwater). Saline water contains a high concentration of dissolved salts (about 35 ppt) compared to fresh water (less than 0.5 ppt). The temperature of the oceans varies mostly as a function of latitude (distance from the equator) and depth. Ocean water is warmer near the equator and less dense than water near the poles. The salinity of the ocean water is also not the same everywhere. This difference in salinity and temperature, together with atmospheric air circulation causes ocean water to move as currents. These global ocean currents have both vertical and horizontal movement and are responsible for climate regulation. An ocean current is defined as a horizontal movement of seawater in the ocean. Ocean currents are driven by the circulation of wind above surface waters interacting with evaporation, sinking of water at high latitudes, and the Coriolis force generated by the earth's rotation. Large surface ocean currents are a response of the atmosphere and ocean to the flow of energy from the tropics to Polar Regions. In some cases, currents are transient features and affect only a small area. Other ocean currents are essentially permanent and extend over large horizontal distances.
One major pattern of ocean currents is the so-called Global Conveyor Belt, or Thermohaline circulation, which has a great impact on global climate (Fig. 8.20). These ocean currents, especially the permanent ones, have a great deal of influence on the water cycle. The Kuroshio Current, off the shores of Japan, is the largest current. It can travel between 40 and 121 kilometers/day, and extends to about 1,000 meters deep. The Gulf Stream is a well-known stream of warm water in the Atlantic Ocean, moving water from the Gulf of Mexico across the Atlantic Ocean towards Great Britain. The flow continues across the Atlantic Ocean towards Great Britain, a current called the North Atlantic drift. Coming from warm climates, the Gulf Stream moves warmer water to the North Atlantic. These warm currents contribute to the higher average temperatures of the East Coast of the United States, Europe, and Scandinavia, which are about 5°C warmer than other land masses at the same latitude. Cornwall, at the southwest corner of Great Britain, is sometimes referred to as the "Cornish Riviera" because of the milder climate attributable to the Gulf Stream.
Figure 8.20. The ocean conveyor belt (thermohaline circulation) showing the major currents [link to the article](http://www.eoearth.org/view/article/51cbef2a7896bb431f69cd56/?topic=51cbfc78f702fc2ba8129e73

The ocean is also home to many forms of life uniquely adapted to survive in this habitat. Unfortunately, humans have degraded the oceans and their life through pollution, overfishing, carbon dioxide acidification and resource exploitation. Figure 8.21 shows a couple of examples of human impacts on the ocean environment.

![Image of ocean pollution](image1)

Figure 8.21: Trash washed up on the beach (A) and seal tangles up and being struggled by plastic trash in the ocean (B).

Watch the video from the Habitable Planet: Oceans Video [video link](http://www.learner.org/courses/envsci/unit/text.php?unit=3&secNum=1

Groundwater

Storage and Flow

Almost 99% of the available fresh water is found below the surface as groundwater. Groundwater is not created by some mysterious processes below ground, but is part of the recycled water in the hydrologic cycle. When precipitation falls, some of the water runs off on the surface while some infiltrates into the ground. Groundwater is replenished when water moves from the surface, through unsaturated rocks or sediment (unsaturated or vadose zone), all the way down the saturated parts (saturated zone or phreatic zone) in a process called infiltration and becomes groundwater (Figure 8.22). The top of the saturated portion is called the water table, which is the boundary between saturated and unsaturated zone.

Groundwater is found in aquifers, which are bodies of rock or sediment that store (and yield) large amounts of usable water in their pores. Aquifer productivity is controlled by porosity and permeability. Porosity is the percentage of open space in a rock or sediment body. Permeability is the ability of subsurface material to transmit fluids. Groundwater is found in the saturated zone of a rock body where all pores are completely filled with water. An important concept is that surface water always moves from higher elevation to lower elevation while groundwater always moves from higher energy (hydraulic head) to lower energy. Hydraulic head is the elevation of water in the subsurface and is a measure of the total energy of the water.
Under most circumstances, ground water at a high elevation has high potential energy than water at lower elevation and, therefore, moves in that direction. So, water in an aquifer will often (but not always) flow from areas of higher elevation to lower elevation.

Figure 8.22: Model of groundwater system showing the different components of an unconfined groundwater system: http://water.usgs.gov/edu/earthgwaquifer.html

There are two kinds of aquifers, unconfined and confined aquifers. An unconfined aquifer is one where the aquifer is open to the surface (has no confining layer above) and water can infiltrate directly into it from any place on the surface above (Figure 8.22 and 8.23).
Figure 8.23: A) A hole dug to the top (water table) of an unconfined Aquifer. B) An aquifer with a water table as the upper boundary (the groundwater divide arrow points to the water table). Photo credit; Jonathan Levy

A **confined aquifer** is one where the saturated material is confined between two impermeable layers above and below, and only has one point of recharge, called a recharge zone (Figure 8.24). Because of having only one area of recharge, confined aquifers are more protected from surface pollution than unconfined aquifers. The confining layer acts as a barrier that keeps contaminants out of the aquifer. Unconfined aquifers do not have this protective barrier and, therefore, any contaminants above the aquifer can get into the aquifer.

Groundwater will continue to flow until it emerges as a spring, or discharges into surface water bodies on the land or in the ocean. To utilize groundwater, we drill holes (wells) into the ground and pump the water out. Sometimes we drill wells called monitoring wells or piezometers to observe and study groundwater. These monitoring wells are usually just open pipes (perforated/slotted at the one end) that are pushed into the ground to allow groundwater to rise up in them (Figure 8.25). When a well is drilled into an unconfined aquifer, the groundwater will rise up to the water table. In a confined aquifer the water rises up above the confining unit to a height equal to the hydraulic head in the aquifer at the well opening.
Water Scarcity and Shortage

Water has been identified as one of the major environmental crisis facing the world today. More than one billion people in the world lack access to clean drinking water, The demand for water has grown at a very fast pace in response to the rate of global population growth. Figures 8.26, 8.27, and 8.28 illustrate this change in water use over time. It is predicted that over the next two decades, the average supply of water per person will drop by a third.
Figure 8.26: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends:

http://water.usgs.gov/edu/wugw.html
Figure 8.27: Both groundwater and surface water withdrawals have increased over time until 1980 when the withdrawals peaked and stabilized.

Figure 8.28: Trends in water withdrawals by water use (US data).
**Water Scarcity and Availability**

There is enough fresh water on Earth to supply every human being with enough drinking water. The main problem we face with regards to water is that it is unevenly distributed, polluted, mismanaged and wasted. Tony Allan, the author of Virtual Water, asserts that water follows money. This refers to the fact that rich countries and societies with money and affluence have more access to safe drinking water even when they live in regions without much water. It also means that areas with large supplies of water can still have water scarcity if they lack the financial resources to build the infrastructure to supply people with safe clean drinking water. Water scarcity is caused by the demand for water being greater than the supply. Scarcity can be defined as either physical scarcity or economic scarcity.

**Physical water scarcity** is a situation where there is an actual shortage of water, regardless of quality or infrastructure. It is estimated that about 1.2 million people around the world are experiencing physical water scarcity. **Economic scarcity** is a condition where countries lack the financial resources and/or infrastructure to supply their citizens with reliable safe drinking water. About 1.6 billion people are experiencing economic water shortage; most of them live in less industrialized countries. For a lot of places in the world, scarcity is a transient condition that can be reduced or eliminated by installing the right infrastructure. The major problem in less industrialized countries is the lack of political, financial and physical structures to provide water to everyone. A few rich people in these countries get the clean water while the majority of the people who cannot afford to pay for it are left out. Examples of such communities include many villages in Africa, Asia, and South America. Figure 8.29 shows communities in south east Kenya that are experiencing severe water shortages primarily due to lack of infrastructure. In these communities women have to walk long distances to get untreated and contaminated water for drinking and other household needs.
Figure 8.29: Communities in southeast Kenya without ready access to safe drinking water. (A) Groundwater in the area is too salty for consumption. B) Maasai women in Amboseli National Park collecting water from a wetland. (C) Women in Magwede village in SE Kenya walking long distances to get water from a Kiosk. D) Children collecting water in Bungule Village from a water kiosk that is only open for about an hour every day. *Photo credit: Jonathan Levy, Sam Mutiti and Christine Mutiti*

**Water Quality (pollution)**

Water pollution is a major problem facing many of our surface water and groundwater sources. Contamination can both be natural due to geologic or meteorological events and anthropogenic (human causes). Human sources of contamination can be categorized as either point source or nonpoint source. **Point-source pollution** is water pollution coming from a single point, such as a sewage-outflow pipe. **Non-point source (NPS) pollution** is pollution discharged over a wide land area such as agricultural runoff and urban stormwater runoff, not from one specific location. Non-point source pollution contamination occurs when rainwater, snowmelt, or irrigation washes off plowed fields, city streets, or suburban backyards. As this runoff moves across the land surface, it picks up soil particles and pollutants, such as nutrients and pesticides.

**Types of Water Pollution**

Contamination of water resources comes in the form of chemical, biological, and physical pollution. **Chemical pollution** include things such as toxic metals, organic compounds, acidic waters from mining activities and industry, pharmaceuticals and many other chemical compounds from industries and wastewater treatment plants. Another form of chemical pollution is radioactive waste which has a significant potential to cause harm to living things. Most of the radioactive pollution comes from agricultural practices such as tobacco farming, where radioactive phosphate fertilizer is used. **Physical pollution** includes sediment pollution, trash thrown in the water bodies, thermal and other suspended load. Temperature typically affects the metabolism of aquatic fauna in a negative way and can encourage eutrophication. **Biological pollution** usually refers to pathogenic bacteria, viruses and parasitic protozoa such as *Giardia*.
**lamblia** and *Cryptosporidium parvum*. Common pathogenic microbes introduced into natural water bodies are pathogens from untreated sewage or surface runoff from intensive livestock grazing. Biological pollution is a common cause of illness and death in less industrialized countries where population density, water scarcity and inadequate sewage treatment combine to cause widespread parasitic and bacterial diseases.

**Sources of water pollution**

Most of the common inorganic chemical water pollutants are produced by non-point sources, mainly intensive agriculture and high-density urban areas. Specific inorganic chemicals and their major sources are: ammonium nitrate and a host of related phosphate and nitrogen compounds used in agricultural fertilizers; heavy metals (present in urban runoff and mine tailings area runoff). However, some inorganics such as chlorine and related derivatives are produced from point sources, ironically employed in water treatment facilities. Moreover, some of the large dischargers of heavy metals to aquatic environments are fixed point industrial plants.

High concentrations of nitrogen (N) and phosphorus (P) in water can cause **eutrophication**. You are seeing this whenever you notice the greenish tint to the water in our local streams and rivers during low-flow times, or if you have ever seen a green farm pond. These nutrients are primarily coming from treated wastewater (laden with P and N) being dumped into the river from sewage plants, from agricultural areas where farmers allow livestock direct access to the stream, from agricultural areas where there is intense fertilizer application, and from landscapes (homes, gardens, golf courses) with fertilizer runoff. The N and P act as fertilizers in the water and promote algae blooms. As the algae dies, it is decomposed by aerobic bacteria in the water. These bacteria use up the oxygen in the water and the low dissolved oxygen (DO) levels can results in fish kill where large numbers of fish, and other aquatic life, die because of suffocation. The dead zone in the Gulf of Mexico is a huge area of low DO that has a large negative impact on the fishing industry along the Gulf Coast near the mouth of the Mississippi River. The dead zone occurs annually when fertilizers, from farm fields in the Midwest, wash down the Mississippi river.

Improper storage and use of automotive fluids produce common organic chemicals causing water pollution. These chemicals include methanol and ethanol (present in wiper fluid); gasoline and oil compounds such as octane, nonane (overfilling of gasoline tanks); most of these are considered non-point sources since their pathway to watercourses is mainly overland flow. However, leaking underground and above ground storage tanks can be considered point sources for some of these chemicals, and even more toxic organic compounds such as perchloroethylene. Grease and fats (such as lubrication and restaurant effluent) can be either point or non-point sources depending upon whether the restaurant releases grease into the wastewater collection system (point source) or disposes of such organics on the exterior ground surface or transports to large landfills.

The most significant physical pollutant is excess sediment in runoff from agricultural plots, clearcut forests, improperly graded slopes, urban streets and other poorly managed lands, especially when steep slopes or lands near streams are involved. Other physical pollutants include a variety of plastic refuse products such as packaging materials; the most pernicious of these items are ring shaped objects that can trap or strangle fish and other aquatic fauna (Figure 8.21). Other common physical objects are timber slash debris, waste paper and cardboard. Finally power plants and other industrial facilities that use natural water bodies for cooling are the main sources of thermal pollution.
Common pathogenic microbes, in addition to *G. lamblia*, are: species of the genus *Salmonella* (which variously cause typhoid fever and food-borne illnesses); species in the genus *Cryptosporidium*, which are fecal-oral route parasites often transmitted as water pollutants and are associated with inadequate sanitation; parasitic worms that live inside faunal digestive systems for part of their life cycle (this widespread syndrome is spread partially as water pollutants, with an estimated three billion people currently affected). Hepatitis A is a viral disease, one of whose pathways of transmission is water-borne.

Groundwater can also become contaminated from both natural and anthropogenic sources of pollution. Naturally occurring contaminants are present in the rocks and sediments. As groundwater flows through sediments, metals such as iron and manganese are dissolved and may later be found in high concentrations in the water. Industrial discharges, urban activities, agriculture, groundwater withdrawal, and disposal of waste all can affect groundwater quality. Contaminants from leaking fuel tanks or fuel or toxic chemical spills may enter the groundwater and contaminate the aquifer. Pesticides and fertilizers applied to lawns and crops can accumulate and migrate to the water table.

Leakage from septic tanks and/or waste-disposal sites also can contaminate ground water. A septic tank can introduce bacteria to the water, and pesticides and fertilizers that seep into farmed soil can eventually end up in water drawn from a well. Or, a well might have been placed in land that was once used as a garbage or chemical dump site.

**Water Management**

**Water pollution control**

Pollution control begins with testing and monitoring of water quality. Water quality is usually monitored using easy to measure indicators such as pH, specific conductance (commonly referred to as conductivity), temperature, fecal and total coliform bacteria, dissolved oxygen, macroinvertebrates, and algae. Polluted sites typically have reduced DO levels, lower pH (more acidic), higher nutrient levels, more bacteria, and higher temperatures compared to less impacted or pristine sites.

Non-point source control relates mostly to land management practices in the fields of agriculture, mining and urban design and sanitation. Agricultural practices leading to the greatest improvement of sediment control include: contour grading, avoidance of bare soils in rainy and windy conditions, polyculture farming resulting in greater vegetative cover, and increasing fallow periods. Minimization of fertilizer, pesticide and herbicide runoff is best accomplished by reducing the quantities of these materials, as well as applying fertilizers during periods of low precipitation. Other techniques include avoiding of highly water soluble pesticides and herbicides, and use of materials that have the most rapid decay times to benign substances.

The main water pollutants associated with mines and quarries are aqueous slurries of minute rock particles, which result from rainfall scouring exposed soils and haul roads and also from rock washing and grading activities. Runoff from metal mines and ore recovery plants is typically contaminated by the minerals present in the native rock formations. Control of this runoff is chiefly achieved by controlling rapid runoff and designing mining operations to avoid tailings either on steep slopes or near streams.

In the case of urban stormwater control, good urban planning and design can minimize stormwater runoff. By reducing impermeable surfaces (pavement that doesn’t allow water through), then cities can reduce the amount of surface water runoff the carries pollutants into
surface water and causes flooding. Additionally, the use of native plant and xeriscape techniques reduces water use and water runoff and also minimizes the need for pesticides and nutrients. In regard to street maintenance, a periodic use of street sweeping can reduce the sediment, chemical and rubbish load into the storm sewer system.

The two common approaches to water management fall under either voluntary programs or the regulatory program. The regulatory approach has been very successful in controlling and reducing point source pollution, which was the main focus of regulations when they were first introduced. Voluntary programs, together with new amendments to regulations, have had great success in increasing conservation and also reducing diffuse nonpoint source pollution. One of the most widely used voluntary programs is Watershed Management while the regulatory approach is centered on the Clean Water Act (CWA).

**Watershed Management**

The watershed management approach recognizes that water contamination problems are complex and not localized to a section of a river. Water pollution problems are caused by multiple activities within the watershed and, therefore, require holistic approaches in the entire watershed. A watershed (drainage basin or catchment) is an area of land that drains to a single outlet and is separated from other watersheds by a drainage divide. Rainfall that falls in a watershed will generate runoff (if not trapped or infiltrated into groundwater) to that watershed’s outlet. Topographic elevation is used to define a watershed boundary. A focal point of water management plans is the Best Management Practices (BMPs) section. BMPs are designed to consider all of the various uses of water, maximize conservation and minimize pollution.

**The regulatory approach**

Water management through policy and laws seeks to clean up polluted water, prevent further pollution and apply punitive measures for polluters. In the US water-related regulations go as far back as 1899 with the Rivers and Harbors Act, also known as the Refuse Act that prohibited the dumping of solid waste and obstruction of waterways. This regulation, however, did not include waste flowing from streets and sewers. In 1948 another regulation, the Federal Water Pollution Act (which is the basis of the Clean Water Act) was enacted. This regulation covered contamination from sewage outfalls. It was created to reduce contamination of both interstate groundwater and surface waters. Through this regulation funding was made available to states and local governments for water quality management.

One of the major water-related regulations in the US is the Clean Water Act (CWA) of 1972. The regulation was very comprehensive with lots of programs and empowered the Environmental Protection Agency (EPA) to create goals, and objective laws for its implementation. The legislation has programs for both point and nonpoint source pollution. One other major piece of regulation governing water was the 1974 Safe Drinking Water Act (SDWA).

In 1974, amended in 1986, the SDWA was enacted to establish standards for many chemical constituents for public water supplied by public water agencies. In the regulations, maximum contaminant level goals (MCLG), which are non-enforceable and maximum contaminant levels (MCLs) that are enforceable where created. MCLG are what would be ideal and desirable while MCL are what should be attained in any drinking water supplied by a public municipal agency. For any carcinogen the MCLG is 0 even though many contaminants have MCLs and detection limits in the parts per billion (ppb) range. Some of them (e.g. dioxin) have
MCLs in the parts per trillion (ppt). To give you a sense of how small this ppt is, it is the same as 0.4 mm divided by the distance to the moon.

**A Closer Look at the Clean Water Act**

The 1972 Clean Water Acts was an overhaul of the 1948 Federal Pollution Control Act. The current regulation includes numerous programs for water quality improvement and protection. The EPA works with its federal, state and tribal regulatory partners to monitor and ensure compliance with clean water laws and regulations in order to protect human health and the environment. The Clean Water Act is the primary federal law governing water pollution. One of the objectives of the CWA was to restore and maintain the integrity of the nation’s physical, chemical and biological waters quality. The ultimate goals of the act are to establish zero pollutant discharge, as well as fishable & swimmable waters in the country. One main component of the CWA is regulations on industrial and municipal discharges into navigable US waters. The act is designed to be a partnership between states and the federal government. The federal government sets the agenda and standards while the state carries out the implementation of the law. States also have the power to set standards that are more stringent than the federal standards if needed. Under the CWA, discharge into US waters is only legal if authorized by a permit. Perpetrators of the law can be punished using administrative, civil or criminal charges. The second component of the act is providing funding for constructing municipal waste water treatment plants and other projects to improve water quality (Title II and Title VI).

The act covers both point sources (discharge from sources such as pipes) and nonpoint sources (pollution from diffuse sources such as stormwater runoff). Point sources are explicitly covered under section 402, National Pollutant Discharge Elimination System (NPDES). This section requires industries and municipalities to get permits from the EPA before discharging into US waters. The permits require the use of control technology to reduce and prevent pollution.

**Water in Crisis (case studies)**

- You instructor will assign you a specific case study for the course.
Bibliography


