The Habitable Planet

Unit 8 : Water Resources

San Pedro River Valley, Arizona.

Overview

Earth's water resources, including rivers, lakes, oceans, and underground aquifers, are under stress in many regions. Humans need water for drinking, sanitation, agriculture, and industry; and contaminated water can spread illnesses and disease vectors, so clean water is both an environmental and a public health issue. In this unit, learn how water is distributed around the globe; how it cycles among the oceans, atmosphere, and land; and how human activities are affecting our finite supply of usable water.

Sections:

The Habitable Planet

1. Introduction

Water resources are under major stress around the world. Rivers, lakes, and underground aquifers supply fresh water for irrigation, drinking, and sanitation, while the oceans provide habitat for a large share of the planet's food supply. Today, however, expansion of agriculture, damming, diversion, over-use, and pollution threaten these irreplaceable resources in many parts of the globe.

Providing safe drinking water for the more than 1 billion people who currently lack it is one of the greatest public health challenges facing national governments today. In many developing countries, safe water, free of pathogens and other contaminants, is unavailable to much of the population, and water contamination remains a concern even for developed countries with good water supplies and advanced treatment systems. And over-development, especially in coastal regions and areas with strained water supplies, is leading many regions to seek water from more and more distant sources (Fig. 1).

Figure 1. Eastern U.S. aquifers contaminated with salt water

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This unit describes how the world's water supply is allocated between major reserves such as oceans, ice caps, and groundwater. It then looks more closely at how groundwater behaves and how scientists analyze this critical resource. After noting which parts of the world are currently straining their available water supplies, or will do so in the next several decades, we examine the problems posed by salinization, pollution, and water-related diseases.

Scientists widely predict that global climate change will have profound impacts on the hydrologic cycle, and that in many cases these effects will make existing water challenges worse. As we will see in detail in Unit 12, "Earth's Changing Climate," rising global temperatures will alter rainfall patterns, making them stronger in some regions and weaker in others, and may make storms more frequent and severe in some areas of the world. Warming will also affect other aspects of the water cycle by reducing the size of glaciers, snowpacks, and polar ice caps and changing rates of evaporation and transpiration. In sum, climate change is likely to make many of the water-management challenges that are outlined in this unit even more complex than they are today.

At the same time, many current trends in water supply and water quality in Europe and North America are positive. Thirty years ago, many water bodies in developed countries were highly polluted. For example, on June 22, 1969, the Cuyahoga River in Cleveland, Ohio, caught fire when sparks ignited an oily slick of industrial chemicals on its surface. Today, the United States and western European countries have reduced pollution discharges into rivers and lakes, often producing quick improvements in water quality. These gains show that when societies make water quality a priority, many polluted sources can be made usable once again. Furthermore, in the United States water consumption rates have consistently declined over the last several decades.

2. The Global Water Cycle

Water covers about three-quarters of Earth's surface and is a necessary element for life. During their constant cycling between land, the oceans, and the atmosphere, water molecules pass repeatedly through solid, liquid, and gaseous phases (ice, liquid water, and water vapor), but the total supply remains fairly constant. A water molecule can travel to many parts of the globe as it cycles.

As discussed in Unit 2, "Atmosphere," and Unit 3, "Oceans," water vapor redistributes energy from the sun around the globe through atmospheric circulation. This happens because water absorbs a lot of energy when it changes its state from liquid to gas. Even though the temperature of the water vapor may not increase when it evaporates from liquid water, this vapor now contains more energy, which is referred to as latent heat. Atmospheric circulation moves this latent heat around Earth, and when water vapor condenses and produces rain, the latent heat is released.

Very little water is consumed in the sense of actually taking it out of the water cycle permanently, and unlike energy resources such as oil, water is not lost as a consequence of being used. However, human intervention often increases the flux of water out of one store of water into another, so it can deplete the stores of water that are most usable. For example, pumping groundwater for irrigation depletes aquifers by transferring the water to evaporation or river flow. Our activities also pollute water so that it is no longer suitable for human use and is harmful to ecosystems.

There are three basic steps in the global water cycle: water precipitates from the atmosphere, travels on the surface and through groundwater to the oceans, and evaporates or transpires back to the atmosphere from land or evaporates from the oceans. Figure 2 illustrates yearly flow volumes in thousands of cubic kilometers.

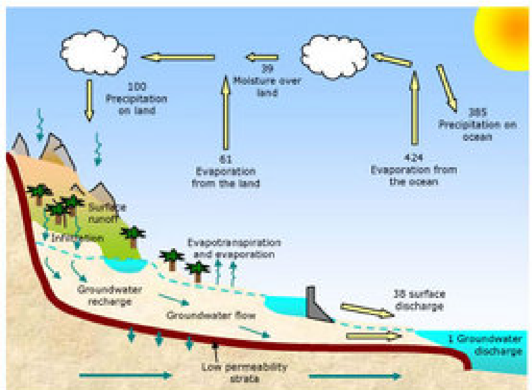

Figure 2. The water cycle

Supplies of freshwater (water without a significant salt content) exist because precipitation is greater than evaporation on land. Most of the precipitation that is not transpired by plants or evaporated, infiltrates through soils and becomes groundwater, which flows through rocks and sediments and discharges into rivers. Rivers are primarily supplied by groundwater, and in turn provide most of the freshwater discharge to the sea. Over the oceans evaporation is greater than precipitation, so the net effect is a transfer of water back to the atmosphere. In this way freshwater resources are continually renewed by counterbalancing differences between evaporation and precipitation on land and at sea, and the transport of water vapor in the atmosphere from the sea to the land.

Nearly 97 percent of the world's water supply by volume is held in the oceans. The other large reserves are groundwater (4 percent) and icecaps and glaciers (2 percent), with all other water bodies together accounting for a fraction of 1 percent. Residence times vary from several thousand years in the oceans to a few days in the atmosphere (Table 1).

Table 1. Estimate of the world water balance.

	Surface area (million km)	Volume (million km)	Volume (%)	Equivalent depth (m)	Residence time
Oceans and seas	361	1,370	94	2,500	~4,000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1-10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks to 50 years
Groundwater	130	60	4	120	2 weeks to 100,000 years
Icecaps and glaciers	17.8	30	2	60	10 to 1,000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

Solar radiation drives evaporation by heating water so that it changes to water vapor at a faster rate. This process consumes an enormous amount of energy—nearly one-third of the incoming solar energy that reaches Earth's surface. On land, most evaporation occurs as transpiration through plants: water is taken up through roots and evaporates through stomata in the leaves as the plant takes in CO_2. A single large oak tree can transpire up to 40,000 gallons per year (footnote 1). Much of the water moving through the hydrologic cycle thus is involved with plant growth.

Since evaporation is driven by heat, it rises and falls with seasonal temperatures. In temperate regions, water stores rise and fall with seasonal evaporation rates, so that net atmospheric input (precipitation minus evaporation) can vary from positive to negative. Temperatures are more constant in tropical regions where large seasonal differences in precipitation, such as monsoon cycles, are the main cause of variations in the availability of water. In an effort to reduce these seasonal swings, many countries have built reservoirs to capture water during periods of high flow or flooding and release water during periods of low flow or drought. These projects have increased agricultural production and mitigated floods and droughts in some regions, but as we will see, they have also had major unintended impacts on water supplies and water quality.

The hydrologic cycle is also coupled with material cycles because rainfall erodes and weathers rock. Weathering breaks down rocks into gravel, sand, and sediments, and is an important source of key nutrients such as calcium and sulfur. Estimates from river outflows indicate that some 17 billion tons of material are transported into the oceans each year, of which about 80 percent is particulate and 20 percent is dissolved. On average, Earth's surface weathers at a rate of about 0.5 millimeter per year. Actual rates may be much higher at specific locations and may have been accelerated by human activities, such as emissions from fossil fuel combustion that make rain and snowfall more acidic.

3. Distribution of Freshwater Resources

Freshwater accounts for only some 6 percent of the world's water supply, but is essential for human uses such as drinking, agriculture, manufacturing, and sanitation. As discussed above, two-thirds of global freshwater is found underground.

If you dig deeply enough anywhere on Earth, you will hit water. Some people picture groundwater as an underground river or lake, but in reality it is rarely a distinct water body (large caves in limestone aquifers are one exception). Rather, groundwater typically fills very small spaces (pores) within rocks and between sediment grains.

The water table is the top of the saturated zone (Fig. 3). It may lie hundreds of meters deep in deserts or near the surface in moist ecosystems. Water tables typically shift from season to season as precipitation and transpiration levels change, moving up during rainy periods or periods of little transpiration and sinking during dry phases when the rate of recharge (precipitation minus evaporation and transpiration that infiltrates from the surface) drops. In temperate regions the water table tends to follow surface topography, rising under hills where there is little discharge to streams and falling under valleys where the water table intersects the surface in the form of streams, lakes, and springs.

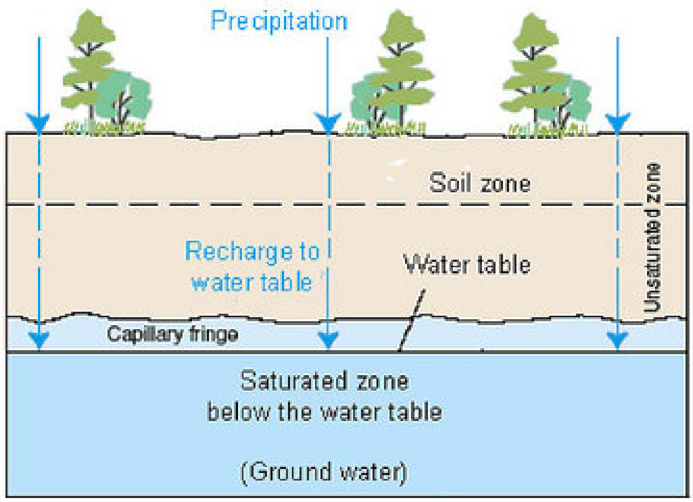

Figure 3. Water in the ground

Above the water table lies the unsaturated zone, also referred to as the vadose zone, where the pores (spaces between grains) are not completely filled with water. Water in the vadose zone is referred to as soil moisture. Although air in the vadose zone is at atmospheric pressures, the soil moisture is under tension, with suctions of a magnitude much greater than atmospheric pressure.

This fluid tension is created by strong adhesive forces between the water and the solid grains, and by surface tension at the small interfaces between water and air. The same forces can be seen at work when you insert a thin straw (a capillary) into water: water rises up in the straw, forming a meniscus at the top. When the straw is thinner, water rises higher because the ratio of the surface area of the straw to the volume of the straw is greater, increasing the adhesive force lifting the water relative to the gravitational force pulling it down. This explains why fine-grained soils, such as clay, can hold water under very large suctions.

Water flows upward under suction through small pores from the water table toward plant roots when evapotranspiration is greater than precipitation. After a rainstorm, water may recharge the groundwater by saturating large pores and cracks in the soil and flowing very quickly downward to the water table.

Millions of people worldwide depend on groundwater stocks, which they draw from aquifers—permeable geologic formations through which water flows easily. Very transmissive geologic formations are desirable because water levels in wells decline little even when pumping rates are high, so the wells do not need to be drilled as deeply as in less transmissive formations and the energy costs of lifting water to the surface are not excessive. Under natural conditions many aquifers are artesian: the water they hold is under pressure, so water will flow to the surface from a well without pumping.

Aquifers may be either capped by an impermeable layer (confined) or open to receive water from the surface (unconfined). Confined aquifers are often artesian because the confining layer prevents upward flow of groundwater, but unconfined aquifers are also artesian in the vicinity of discharge areas. This is why groundwater discharges into rivers and streams. Confined aquifers are less likely to be contaminated because the impermeable layers above them prevent surface contaminants from reaching their water, so they provide good-quality water supplies (Fig. 4).

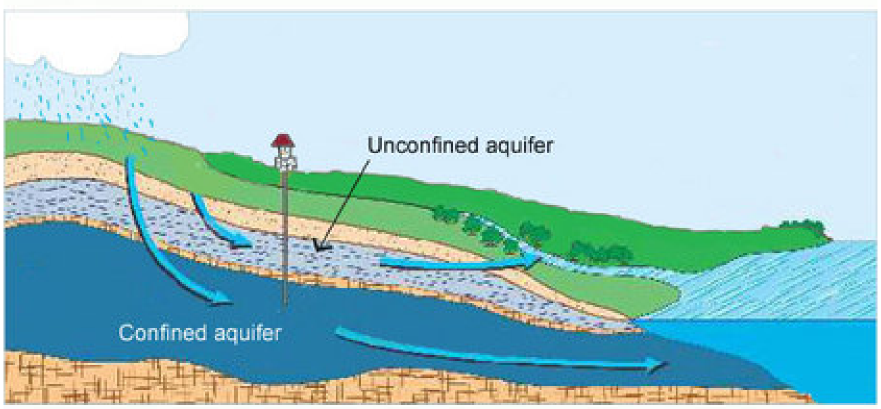

Figure 4. Confined and unconfined aquifer

Water has an average residence time of thousands to tens of thousands of years in many aquifers, but the actual age of a water sample collected from a particular well will vary tremendously within an aquifer. Shallow groundwater can discharge into streams and rivers in weeks or months, but some deep groundwater is millions of years old—as old as the rocks that hold the water in their pores. Because of this distribution of residence times in aquifers, contaminants that have been introduced at the surface over the last century are only now beginning to reach well depths and contaminate drinking water in many aquifers. Indeed, much of the solute load (salt and other contaminants) that has entered aquifers due to increased agriculture and other land use changes over the last several centuries has yet to reach discharge areas where it will contaminate streams and lakes (footnote 2).

Ice sheets and glaciers are not always thought of as freshwater sources, but they account for a significant fraction of world reserves. Nearly 90 percent of the water in icecaps and glaciers is in Antarctica, with another 10 percent in the Greenland ice sheet and the remainder in tropical and temperate glaciers. As discussed in Unit 1, "Many Planets, One Earth," and Unit 12, "Earth's Changing Climate," Earth's ice sheets constantly expand and contract as the planet's climate fluctuates. During warm periods ice sheets melt and sea levels rise, with the reverse occurring when temperatures fall. Water may remain locked in deep layers of polar ice sheets for hundreds of thousands of years.

Rivers contain a relatively small share of fresh water, but the flux of water down rivers is a large part of the global hydrologic cycle and they are centrally important in shaping landscapes. Their flow erodes solid sediment and carries it toward the sea, along with dissolved minerals. These processes shape land into valleys and ridges and deposit thick layers of sediment in flood plains. Over geologic time the erosion caused by rivers balances the uplift driven by plate tectonics. Much of Earth's freshwater flow passes through several of the planet's largest rivers: the Amazon carries 15 percent of total river flow on Earth, the Congo carries 3.5 percent, and rivers that flow into the Arctic Ocean carry 8 percent. The average residence time of water in rivers is less than a year.

4. Groundwater Hydrology: How Water Flows

How does water move through the ground and interact with sediments and rock? Will an aquifer recharge slowly or quickly after water is withdrawn, and where will new groundwater come from? These questions are central for communities that need adequate drinking water, farmers tending crops and livestock, and engineers working to keep water supplies free of contaminants. For example, the 1986 trial recounted in the book and movie **A Civil Action** focused on town drinking wells in Woburn, Massachusetts, that were polluted with industrial chemicals suspected of causing cancer among residents. Plaintiffs asserted—and an investigation by the Environmental Protection Agency ultimately confirmed—that chemicals dumped by several local businesses had flowed through groundwater to the underlying aquifer and contaminated the wells (footnote 3).

The pore structure of soils, sediment, and rock is a central influence on groundwater movement. Hydrologists quantify this influence primarily in terms of:

- porosity: the proportion of total volume that is occupied by voids, like the spaces within a pile of marbles. Porosity is not a direct function of the size of soil grains—the porosity of a pile of basketballs is the same as a pile of marbles. Porosity tends to be larger in well sorted sediments where the grain sizes are uniform, and smaller in mixed soils where smaller grains fill the voids between larger grains. Soils are less porous at deeper levels because the weight of overlying soil packs grains closer together.

- permeability: how readily the medium transmits water, based on the size and shape of its pore spaces and how interconnected its pores are.

Materials with high porosity and high permeability, such as sand, gravel, sandstone, fractured rock, and basalt, produce good aquifers. Low-permeable rocks and sediments that impede groundwater flow include granite, shale, and clay.

Groundwater recharge enters aquifers in areas at higher elevations (typically hill slopes) than discharge areas (typically in the bottom of valleys), so the overall movement of groundwater is downhill. However, within an aquifer, water often flows upward toward a discharge area (Fig. 5). To understand and map the complex patterns of groundwater flow, hydrogeologists use a quantity called the hydraulic head. The hydraulic head at a particular location within an aquifer is the sum of the elevation of that point and the height of the column of water that would fill a well open only at that point. Thus, the hydraulic head at a point is simply the elevation of water that rises up in a well open to the aquifer at that point.

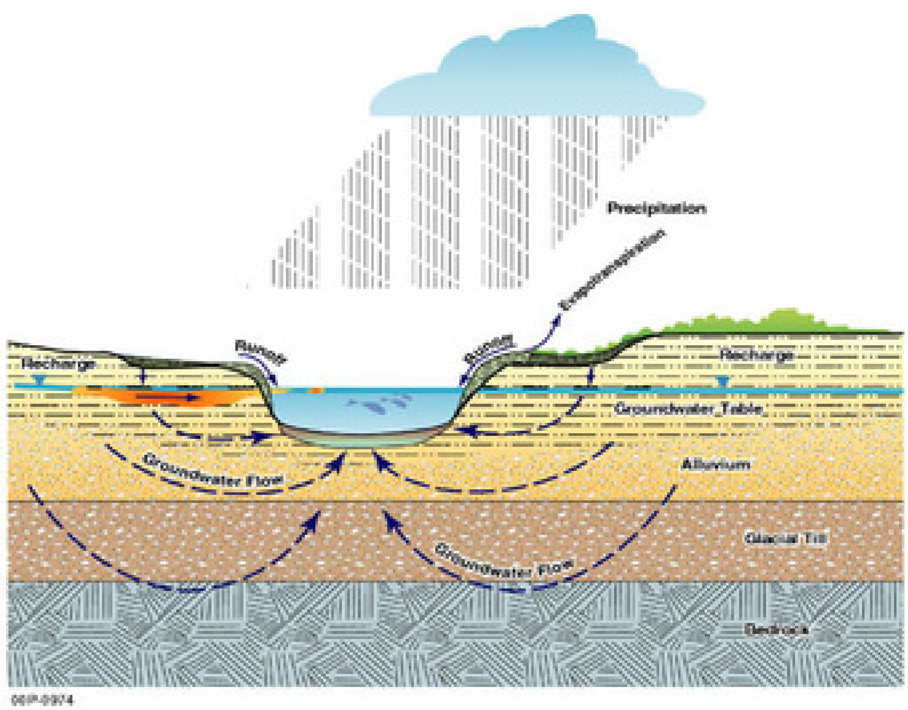

Figure 5. Groundwater flow under the Housatonic River, Pittsfield, Massachusetts

The height of water within the well is not the same as the distance to the water table. If the aquifer is under pressure, or artesian, this height may be much greater than the distance to the water table. Thus the hydraulic head is the combination of two potentials: mechanical potential due to elevation, like a ball at the top of a ramp, and pressure potential, like air compressed in a balloon. Because these are usually the only two significant potentials driving groundwater flow, groundwater will flow from high to low hydraulic head.

This theory works in the same way that electrical potential (voltage) drives electrical flow and thermal potential (temperature) drives heat conduction. Like these other fluxes, groundwater flux between two points is simply proportional to the difference in potential, hydraulic head, and also to the permeability of the medium through which flow is taking place. These proportionalities are expressed in the fundamental equation for flow through porous media, known as Darcy's Law.

The gradient in hydraulic potential may drive groundwater flow downward, upward, or horizontally. Hydrogeologists collect water levels measured in wells to map hydraulic potential in aquifers. These maps can then be combined with permeability maps to determine the pattern in which groundwater flows throughout the aquifer.

Depending on local rainfall, land use, and geology, streams may be fed by either groundwater discharge or surface runoff and direct rainfall, or by some combination of surface and groundwater. Perennial streams and rivers are primarily supplied by groundwater, referred to as baseflow. During dry periods they are completely supplied by groundwater; during storms there is direct runoff and groundwater discharge also increases. The hydrograph in Figure 6 shows flow patterns in a stream before, during, and after a storm with relative contributions from groundwater (baseflow) and surface water (quickflow, also referred to as storm flow).

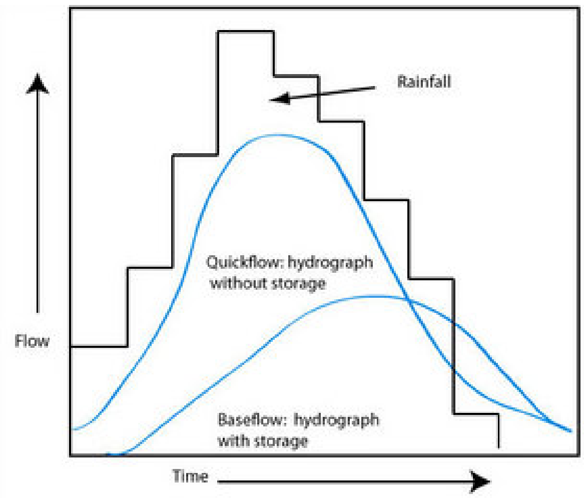

Figure 6. Components of a typical flood hydrograph

5. World Demand for Water

How much water do humans use? The answer depends on where they live and on their socioeconomic status. Under primitive conditions a person will consume three to five gallons per day for drinking and subsistence farming. In a city where water is also used for cleaning, manufacturing, and sanitation, per capita use is around 150 gallons per day. In the United States, which has among the highest water consumption rates in the world, each person uses an average of 1,340 gallons of water per day. Table 2 shows how much water is required to produce common goods and services.

Table 2. Average water requirements.

Item	Gallons used
1 pound of cotton	2,000
1 pound of grain-fed beef	800
1 loaf of bread	150
1 car	100,000
1 kilowatt hour of electricity	25
1 pound of rubber	100

Item	Gallons used
1 pound of steel	25
1 gallon of gasoline	10
1 load of laundry	60
1 ten-minute shower	25-50

As discussed in Unit 2, "Atmosphere," and Unit 3, "Oceans," water resources are not distributed evenly in space or time around the world. Global circulation patterns create wet and dry climate zones, and in some regions seasonal or multi-annual climate cycles generate distinct wet and dry phases. As a result, some regions have larger freshwater endowments than others (Fig. 7).

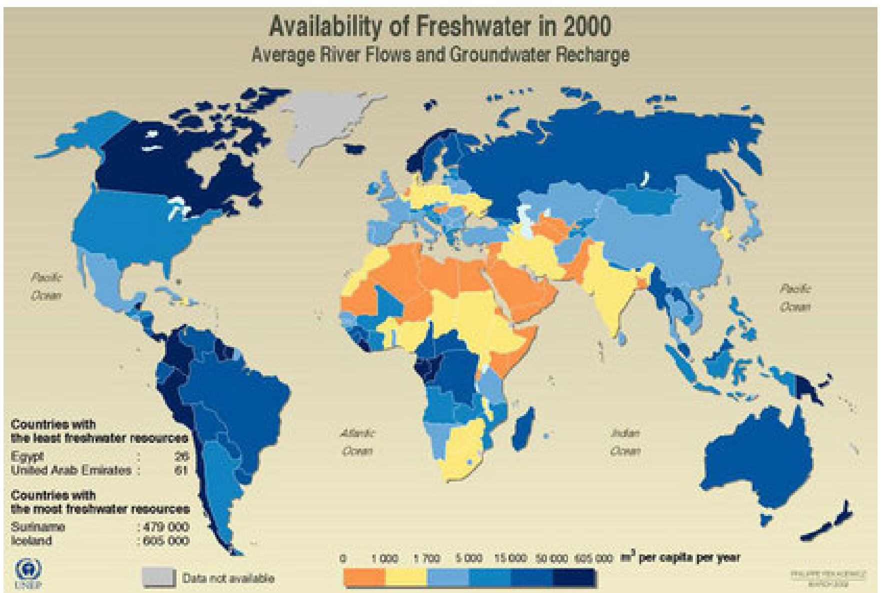

Figure 7. World freshwater supplies

Although developed nations generally have more water available than many countries in Africa and the Middle East, some areas with good water endowments still are subject to "water stress" because they are withdrawing water from available supplies at extremely high rates (Fig. 8). High-intensity water uses in industrialized nations include agricultural production and electric power generation, which requires large quantities of water for cooling. In the United States electric power production accounts for 39 percent of all freshwater withdrawals (footnote 4), although almost all of this water is immediately returned to the rivers from which it is withdrawn. Agriculture consumes much more water because irrigation increases transpiration to the atmosphere.

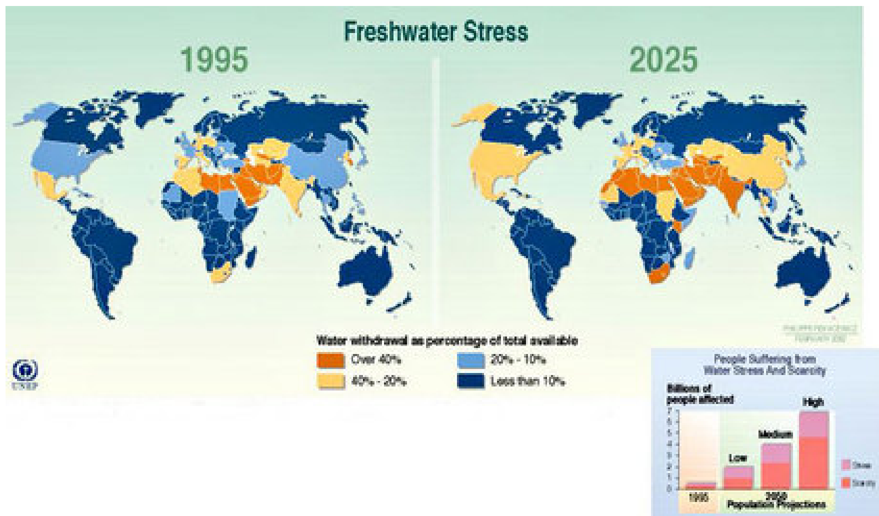

Figure 8. Current and projected freshwater stress areas

As of 2002, 1.1 billion people around the world (17 percent of global population) did not have access to safe drinking water and 2.6 billion people (42 percent of global population) lived without adequate sanitation. As a result, millions of people die each year of preventable water-related diseases. Most of the countries with inadequate supplies of safe drinking water are located in Africa, Asia, and the Pacific, but problems persist elsewhere as well. For example, many households lack adequate sewage treatment services in Eastern Europe. And inequity among water users is widespread: cities often receive better service than rural areas, and many poor communities in both rural and urban areas lack clean water and sanitation (footnote 5).

Although these challenges apply in many regions, it is hard to make broad generalizations about water resources at the global or national level; to paraphrase the famous saying about politics, all hydrology is local. The basic geologic unit that scientists focus on to characterize an area's water supply and water quality with precision is the watershed or catchment area—an area of land that drains all streams and rainfall to a common outlet such as a bay or river delta. Large watersheds, such as the Amazon, the Mississippi, and the Congo contain many smaller sub-basins (footnote 6).

To see why water issues are best studied at the watershed level, consider Washington State, which is divided centrally by the Cascade Mountains. West of the Cascades, Washington receives up to 160 inches of rainfall annually, and the mild, humid climate supports temperate rainforests near the Pacific coast. Across the Cascades, rainfall is as low as six inches per year in the state's semiarid interior where groundwater is pumped from deep within basalt formations to grow wheat (Fig. 9). Urban Seattle residents and ranchers in rural eastern Washington thus face very different water supply, runoff, and water quality issues.

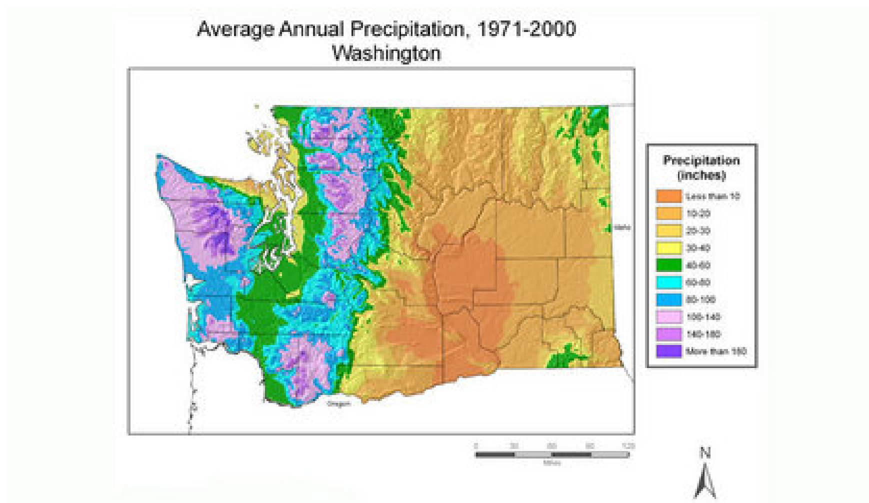

Figure 9. Average annual precipitation, Washington, 1971–2000

Currently 10,000 to 12,000 cubic kilometers of freshwater are available for human consumption each year worldwide. In the year 2000 humans withdrew about 4,000 km^3 from this supply. About half of the water withdrawn was consumed, meaning that it was evaporated, transpired by plants, or contaminated beyond use, and so became temporarily unavailable for other users. The other 50 percent was returned to use: for example, some water used for irrigation drains back into rivers or recharges groundwater, and most urban wastewater is treated and returned to service.

Of the water withdrawn for human use, 65 percent went to agriculture, 10 percent to domestic use (households, municipal water systems, commercial use, and public services), 20 percent to industry (mostly electric power production), and 5 percent evaporated from reservoirs (footnote 7). About 70 percent of the water used for agriculture was consumed, compared to 14 percent of water used for domestic consumption and 11 percent of water used for industry.

Both population levels and economic development are important drivers of world water use. If current patterns continue, the World Water Council estimates that total yearly withdrawals will rise to more than 5,000 km^3 by 2050 as world population rises from 6.1 billion to 9.2 billion. During the 20th century, world population tripled but water use rose by a factor of six (footnote 8). The United Nations and the international community have set goals of halving the number of people without adequate safe drinking water and sanitation by 2015. Meeting this target will require providing an additional 260,000 people per day with clean drinking water and an additional 370,000 people per day with improved sanitation through the year 2014, even as overall world demand for water is rising (footnote 9).

6. Depletion of Freshwater Resources

In many parts of the world people are extracting water from aquifers more quickly than the aquifers are replenished by recharge. In addition to draining aquifers, excessive groundwater pumping changes groundwater flow patterns around wells and can drain nearby rivers and streams. This happens because pumping changes the natural equilibrium that exists in an undeveloped aquifer with discharge balancing recharge.

When pumping starts, groundwater stores are depleted in the vicinity of the well, creating a cone of depression in the hydraulic head. If a new water source such as a river or stream is available close by, the well may capture (draw water from) that source and increase its recharge rate (Fig. 10) until this inflow matches the pumping rate. If no such source is available and pumping draws the water table down far enough, it will dry up the aquifer or deplete it so far that is it not physically possible or affordable to pump out the last stores of water.

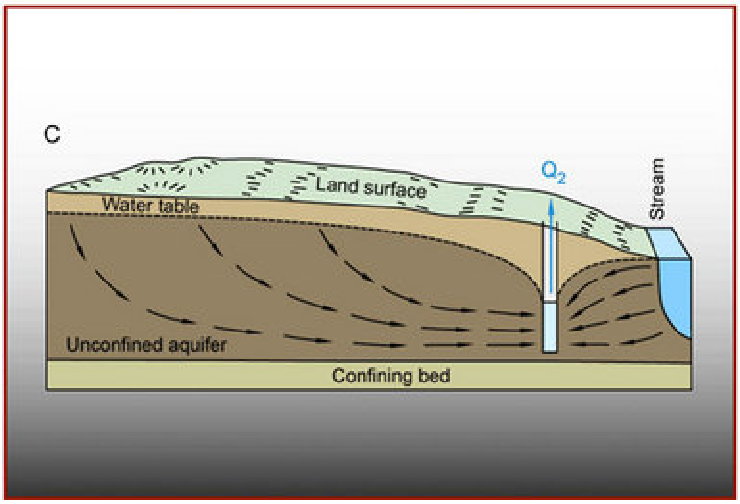

Figure 10. Effects of groundwater pumping

Pumping quickly lowers the pressure within confined aquifers so that water no longer rises to the surface naturally. Fifty years ago artesian aquifers were common, but today they have become rare because of widespread groundwater withdrawals. In unconfined aquifers, air fills pores above the water table, so the water table falls much more slowly than in confined aquifers.

As aquifers are depleted, water has to be lifted from much greater depths. In some parts of the world, the energy costs of lifting groundwater from deep beneath the surface have become prohibitive. Overuse of groundwater can also reduce the quality of the remaining water if wells draw from contaminated surface sources or if water tables near the coast drop below sea level, causing salt water to flow into aquifers.

Serious groundwater depletion has occurred in major parts of North Africa, the Middle East, South and Central Asia, North China, North America, and Australia, along with other localized areas worldwide (footnote 10). In some cases, such as the Ogallala aquifer in the central United States, water tables are falling so low that wells can no longer produce water. In a draft plan issued in mid-2006, the Texas Water Development Board projected that the state's water supplies would fall by about 18 percent between 2010 and 2060, "primarily due to the accumulation of sediments in reservoirs and the depletion of aquifers," and that at the same time the state's population would more than double. If Texas did not implement the water management plan, the board estimated, water shortages could cost the state nearly $100 billion by 2060 (footnote 11).

Many rivers around the globe have also been depleted by increasing water withdrawals. Some, such as the Colorado and Rio Grande, no longer reach the sea during much of the year because their flow levels have been reduced so drastically by dams and water diversion (Fig. 11). This overuse destroys estuaries at river mouths, which are important habitats and breeding grounds for fish and birds.

Figure 11. Dams and diversions along the Rio Grande

Under normal conditions, most rivers are gaining rivers: groundwater flows into the rivers because the local water table sits at a higher elevation than the river water. However, with excessive groundwater pumping, water tables slowly decline and natural discharge to the rivers is reduced, so river flow declines. Over the long term, groundwater extraction may greatly reduce river flows in many regions. This connection between water levels in aquifers and river flows complicates the process of estimating sustainable yield from aquifers. If users pump more water from an aquifer than the natural rate of recharge, the aquifer may draw water from adjoining rivers and increase its rate of recharge. However, by doing so it will reduce surface water flows.

Almost every country in the world that uses groundwater as a resource is having troubles with it affecting surface water systems.

Tom Maddock, University of Arizona

By regulating river flows to reduce floods and increase flows during dry periods, dams have major impacts on river ecosystems. Like forest fires, river floods play important ecological roles that we have only begun to appreciate and foster in recent decades. Among other services, floods scour out channels, deposit nutrient-rich sediments on flood plains, and help to replenish groundwater.

In regions where rivers have been channeled between levees to prevent flooding, they no longer deposit sediments and nutrients on surrounding lands. Scientists widely agree that damage from Hurricane Katrina in August 2005 was magnified because levees and canals around New Orleans had directed the Mississippi River's flow straight into the Gulf of Mexico for decades. Without fresh water and sediment from the Mississippi, southern Louisiana's wetlands degraded and subsided, reducing their ability to buffer the region against storms and flooding.

7. Water Salinization

When freshwater resources become saline, they can no longer be used for irrigation or drinking. Saline water is toxic to plants, and high sodium levels cause dry soils to become hard and compact and reduce their ability to absorb water. Irrigation water becomes toxic to most plants at concentrations above 1,300 milligrams/liter; for comparison, the salinity of seawater is about 35,000 mg/l (footnote 12). Salinity is not dangerous to humans, but water becomes nonpotable for human consumption at about 250 mg/l.

Groundwater extraction and irrigation can increase salt concentrations in water and soils in several ways. First, irrigation increases the salinity of soil water when evaporation removes water but leaves salt behind. This occurs when irrigation water contains some salt and irrigation rates are not high enough to flush the salt away. Saline water in the vadose zone can then contaminate surface water and soils. Irrigation has caused high salinity levels in areas including the cotton growing region near the Aral Sea in Central Asia, the lower reaches of the Colorado River, and California's Central Valley (Fig. 12).

Figure 12. Fields in central California suffering from severe salinization

Irrigation can also cause salinization by raising the water table and lifting saline groundwater near the surface into the root zone. This occurs when irrigation efficiency is poor, so a large fraction of irrigation water infiltrates into the soil, and groundwater flow is slow. A similar problem occurs in some regions when trees are cut down, reducing transpiration and increasing the rate at which water flushes through the vadose zone. The increased infiltration flushes high concentrations of salt to the water table and lifts the water table toward the surface. This process has severely affected the Murray-Darling Basin in Australia.

A third type of salinization occurs in coastal areas, where excessive groundwater pumping draws seawater into aquifers and contaminates wells. In coastal aquifers freshwater floats on top of denser seawater. When this lens of freshwater is diminished by withdrawals, seawater rises up from below. Because world populations are increasing particularly rapidly in coastal regions, seawater intrusion is a threat in many coastal aquifers.

A recent analysis by scientists at the Institute of Ecosystem Studies found that salinity levels have also increased significantly in urban and suburban areas in the northeastern United States. The authors attributed this rise to two main factors: use of salts for de-icing roads in winter and increased levels of street paving. These trends deliver concentrated bursts of saline runoff to local water bodies after storms and floods. "As coverage by impervious surfaces increases, aquatic systems can receive increased and pulsed applications of salt, which can accumulate to unsafe levels in ground and surface waters over time," the authors observe (footnote 13).

8. Water Pollution

Many different types of contaminants can pollute water and render it unusable. Pollutants regulated in the United States under national primary drinking water standards (legally enforceable limits for public water systems to protect public health) include:

- **Microorganisms** such as cryptosporidium, giardia, and fecal coliform bacteria
- **Disinfectants and water disinfection byproducts** including chlorine, bromate, and chlorite
- **Inorganic chemicals** such as arsenic, cadmium, lead, and mercury
- **Organic chemicals** such as benzene, dioxin, and vinyl chloride
- **Radionuclides** including uranium and radium

These pollutants come from a wide range of sources. Microorganisms are typically found in human and animal waste. Some inorganic contaminants such as arsenic and radionuclides such as uranium occur naturally in geologic deposits, but many inorganic and most major organic pollutants are emitted from industrial facilities, mining, and agricultural activities such as fertilizer and pesticide application.

Sediments (soil particles) from erosion and activities such as excavation and construction also pollute rivers, lakes, and coastal waters. As discussed in Unit 3, "Oceans," availability of light is the primary constraint on photosynthesis in aquatic ecosystems, so adding sediments can severely affect productivity in these ecosystems by clouding the water. It also smothers fish and shellfish spawning grounds and degrades habitat by filling in rivers and streams (Fig. 13).

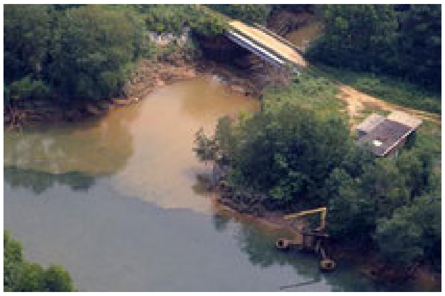

Figure 13. Sedimentation in Chattahoochee River, Atlanta, Georgia

The Habitable Planet

Water supplies often become polluted because contaminants are introduced into the vadose zone or are present there naturally and penetrate to the water table or to groundwater, where they move into wells, lakes, and streams. Many dissolved compounds can be toxic and carcinogenic, so keeping them out of water supplies is a central public-health goal. One critical question is how compounds of concern behave in water. Non-aqueous phased liquids (NAPLs) form a separate phase that does not mix with water and can reside as small blobs within the pore structure of aquifers and soils. Some, such as gasoline and diesel fuel, are lighter than water and will float on top. Others, including chlorinated hydrocarbons and carbon tetrachloride, are denser and will sink. Both types are difficult to remove and will slowly dissolve into groundwater, migrating downgradient as groundwater flows.

Other contaminants completely dissolve in water and, if they enter the aquifer at a single location (e.g., from a point source), are transported with flowing groundwater as plumes that gradually mix with native groundwater (Fig. 14). Over time, contaminated zones become larger but concentrations fall as the plume spreads. The paths that plumes follow can be extremely complex because of the complicated patterns of permeability within aquifers. Groundwater velocities are much higher through channels of high permeability, so these channels transport dissolved contaminants rapidly through the subsurface.

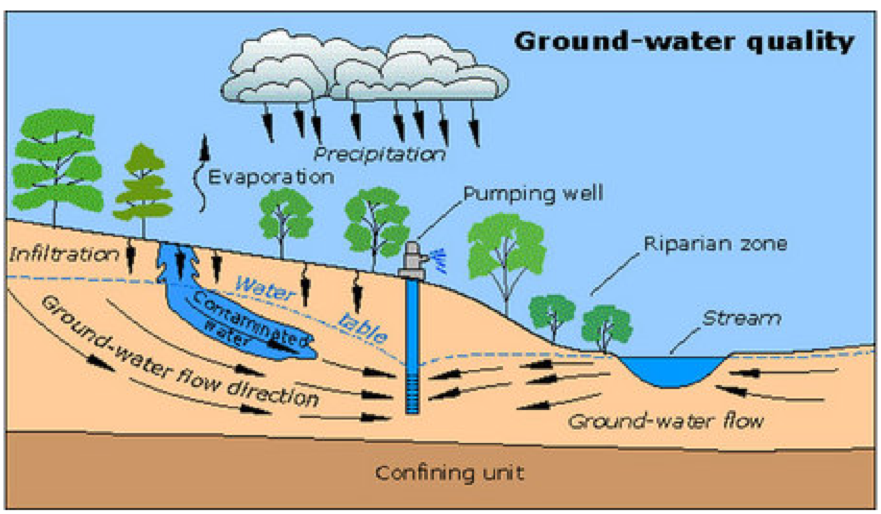

Figure 14. Contaminant flow in groundwater

As a plume moves through groundwater, some contaminants in it may bind to soil particles, a process called sorption. High organic material and clay content in soils generally increases sorption because these particles are chemically reactive and have large surface areas. Sorption may prevent contaminants from migrating: for example, in some spills containing uranium, the uranium has moved only a few meters over decades. However, contaminants like uranium can also adsorp to very small suspended particles called colloids that migrate easily through aquifers. Even if a contaminated plume is pumped out, sorbed contaminants may remain on the solid matrix to desorb later back into the groundwater, so sorption makes full cleanup of the contamination more expensive and time-consuming.

Water pollution is relatively easier to control when it comes from a point source—a distinct, limited discharge source such as a factory, which can be required to clean up or reduce its effluent. Nonpoint source pollution consists of diffuse, nonbounded discharges from many contributors, such as runoff from city streets or agricultural fields, so it is more challenging to control.

Approaches for controlling nonpoint source pollution include improving urban stormwater management systems; regulating land uses; limiting broad application of pesticides, herbicides, and fertilizer; and restoring wetlands to help absorb and filter runoff (Box 1). U.S. regulations are increasingly emphasizing limits on total discharges to water bodies from all sources (for details, see the discussion of Total Maximum Daily Loads below in Section 10, "Major Laws and Treaties").

Along with freshwater bodies, many coastal areas and estuaries (areas where rivers meet the sea, mixing salt and fresh water) are severely impacted by water pollution and sedimentation. Ocean pollution kills fish, seabirds, and marine mammals; damages aquatic ecosystems; causes outbreaks of human illness; and causes economic damage through impacts on activities such as tourism and fishing.

A 2000 National Research Council report cited nutrient pollution (excess inputs of nitrogen and phosphorus) as one of the most important ocean pollution problems in the United States (footnote 14). As discussed in Unit 3, "Oceans," and Unit 4, "Ecosystems," nutrient-rich runoff into ocean waters stimulates plankton to increase photosynthesis and causes "blooms," or population explosions. When excess plankton die and sink, their decomposition consumes oxygen in the water.

Since the beginning of the industrial age, human activities, especially fertilizer use and fossil fuel combustion, have roughly doubled the amount of nitrogen circulating globally, increasing the frequency and size of plankton blooms. This process can create hypoxic areas ("dead zones"), where dissolved oxygen levels are too low to support marine life—typically less than two to three milligrams per liter. Seasonal dead zones regularly appear in many parts of the world. One of the largest, in the Gulf of Mexico, covers up to 18,000 square kilometers each summer, roughly the size of New Jersey (Fig. 15), where river and groundwater flow deliver excess nutrients from upstream agricultural sources to the coast.

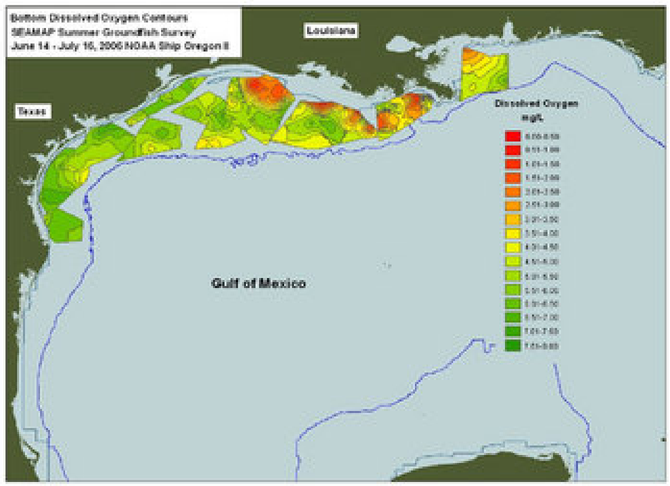

Figure 15. Gulf of Mexico Dead Zone, July 2006

9. Water-Related Diseases

More than 2 million people die each year from diseases such as cholera, typhoid, and dysentery that are spread by contaminated water or by a lack of water for hygiene. These illnesses have largely been eradicated in developed nations, although outbreaks can still occur. In 1993 an infestation of cryptosporidium, a protozoan that causes gastrointestinal illness, killed 110 people and sickened an estimated 400,000 in Milwaukee, Wisconsin. The city's water treatment system was in compliance with federal and state regulations at the time, but after the outbreak federal regulators increased testing requirements for turbidity (cloudiness) in drinking water, an indicator of possible contamination.

Water-related illnesses fall into four major categories:

- **Waterborne diseases**, including cholera, typhoid, and dysentery, are caused by drinking water containing infectious viruses or bacteria, which often come from human or animal waste.

- **Water-washed diseases**, such as skin and eye infections, are caused by lack of clean water for washing.
- **Water-based diseases**, such as schistosomiasis, are spread by organisms that develop in water and then become human parasites. They are spread by contaminated water and by eating insufficiently cooked fish.
- **Water-related insect vectors**, such as mosquitoes, breed in or near water and spread diseases, including dengue and malaria. This category is not directly related to water supply or quality.

As noted above, more than 1 billion people worldwide lack safe drinking water, mainly in developing countries. Conventional large-scale engineering projects that pipe water from central distribution systems can provide safe water at a cost of approximately $500 per person. Small-scale approaches, such as drilling wells and chlorination, can reduce this cost to less than $50 (Fig. 16).

Figure 16. Sodium hypochlorite solution for disinfecting water

Scientists are still learning how many water-related diseases spread and how infectious agents behave. For example, until the 1970s cryptosporidium was not believed to infect humans, although it was recognized as a threat to animals. A 2003 World Health Organization report on water-related infectious diseases warned that "the spectrum of disease is altering and the incidence of many water-related microbial diseases is increasing." Processes such as urbanization and dam construction can spread water-related diseases by creating new environments for infectious agents, and global climate change is expanding the range of mosquitoes and other disease vectors. However, advances in microbiology are enabling researchers to detect pathogens in water more quickly and to identify and characterize new infectious agents (footnote 15).

10. Major Laws and Treaties

The central U.S. law regulating water quality is the Clean Water Act (CWA), adopted in 1972. The Act initially focused on point sources, which it regulates through a national program that requires sources to obtain permits for any discharges of controlled pollutants into the nation's "navigable waters." It also increased federal aid to states and localities for sewage treatment facilities. One contentious issue in recent years has been CWA protection for wetlands. Developers have filed multiple lawsuits over issues such as whether isolated and seasonal wetlands fall under the definition of "navigable waters" and whether various types of dredging and filling constitute discharges into wetlands.

The CWA permitting system has substantially reduced water pollution from point sources in the United States, but nonpoint source pollution remains a serious problem. Since the mid-1990s the Environmental Protection Agency has increasingly focused on requirements in the CWA for states to identify "impaired" water bodies (those that remain polluted even after point sources install technical controls) and to develop Total Maximum Daily Load (TMDL) requirements for these systems. Some 20,000 water bodies across the nation fall under this heading (Fig. 17).

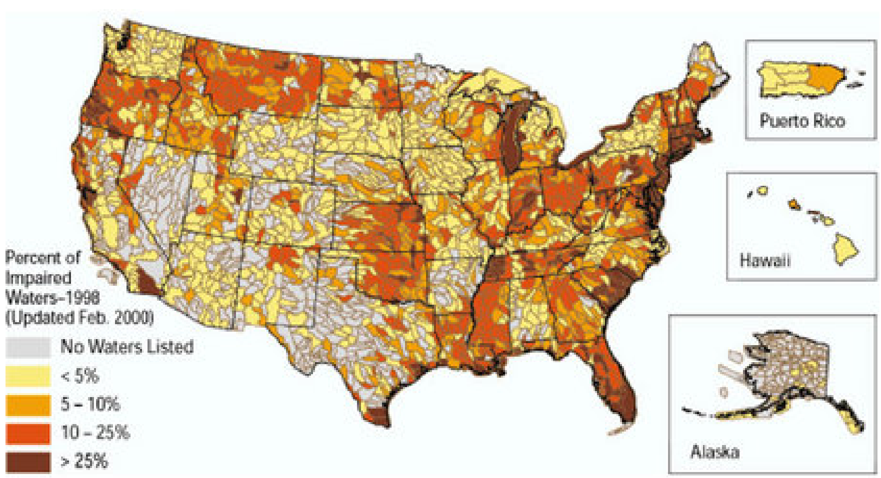

Figure 17. Impaired U.S. waters, 2000

TMDLs represent the maximum levels of specific pollutants that can be discharged into impaired water bodies from all point and nonpoint sources, including a safety margin. Once states calculate TMDLs they must assign discharge limits to all sources and develop pollution reduction strategies (footnote 16). TMDLs are difficult and expensive to calculate because state regulators need extensive data on all polluters that are discharging into impaired water bodies and must quantify relative contributions from all sources to total pollution.

The Safe Drinking Water Act (SDWA), enacted in 1974, regulates contaminants in public water supplies, which serve about 90 percent of the U.S. population. The law sets mandatory limits on some 90 contaminants to protect public health and recommends voluntary standards for other substances that can affect water characteristics such as odor, taste, and color (footnote 17). The SDWA has significantly improved the quality of drinking-water supplies, but new issues are still emerging. For example, methyl tertiary butyl ether (MTBE), an additive widely used to improve combustion in gasoline, has contaminated public water supplies in many regions where gasoline has leaked from underground storage tanks. The EPA has issued a drinking water advisory for MTBE because small amounts can cause discoloration and odor that make water unpotable, but has not yet set a drinking water standard for MTBE even though the agency's Office of Research and Development calls MTBE "a possible human carcinogen." As of 2004, 19 states had acted independently to ban or limit use of MTBE (footnote 18).

At the international level, the United Nations Convention on the Law of the Sea (LOS Convention), finalized in 1982, creates a comprehensive framework for nations' use of the oceans. The convention outlines each country's rights and responsibilities within its territorial boundaries and in international waters for issues including pollution control, scientific research, resource management, and seabed mining. Coastal states have jurisdiction to protect the marine environment in their Exclusive Economic Zones (areas typically extending 200 miles outward from shore) from activities including coastal development, offshore drilling, and pollution from ships.

The United States is not among the 149 nations that have ratified the convention, which President Reagan refused to sign in 1982, citing restrictions on deep seabed mining that were later renegotiated to address U.S. concerns. Two expert commissions and many stakeholders have called for the United States to ratify the pact (footnote 19). The United States is a party to a number of other international treaties and agreements that regulate ocean activities, including agreements on dumping pollutants at sea, protecting the Arctic and Antarctic environments, regulating whaling, and protecting endangered species.

11. Further Reading

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Footnotes

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11. Texas Water Development Board, 2007 Draft State Water Plan, http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/Draft_2007SWP.htm, p. 3.

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13. Sujay S. Kaushal et al., "Increased Salinization of Fresh Water in the Northeastern United States," **Proceedings of the National Academy of Sciences**, vol. 102, September 20, 2005, p. 13517.

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Glossary

aquifers : Underground formations, usually composed of sand, gravel, or permeable rock, capable of storing and yielding significant quantities of water.

artesian : Describes a confined aquifer containing groundwater that will flow upwards out of a well without the need for pumping.

catchment area : The area that draws surface runoff from precipitation into a stream or urban storm drain system.

discharges : Defined by the Clean Water Act as the addition of pollutants (including animal manure or contaminated waters) to navigable waters.

estuaries : Coastal waters where seawater is measurably diluted with freshwater; a marine ecosystem where freshwater enters the ocean.

freshwater : Water without significant amounts of dissolved sodium chloride (salt). Characteristic of rain, rivers, ponds, and most lakes.

groundwater : Water contained in porous strata below the surface of the Earth.

hydraulic head : The force per unit area exerted by a column of liquid at a height above a depth (and pressure) of interest. Fluids flow down a hydraulic gradient, from points of higher to lower hydraulic head.

hypoxic : Referring to a condition in which natural waters have a low concentration of dissolved oxygen (about 2 milligrams per liter, compared with a normal level of 5 to 10 milligrams per liter). Most game and commercial species of fish avoid waters that are hypoxic.

non-aqueous phased liquids (NAPL) : Organic liquids that are relatively insoluble in water and less dense than water. When mixed with water or when an aquifer is contaminated with this class of pollutant (frequently hydrocarbon in nature), these substances tend to float on the surface of the water.

nonpoint source : A diffuse, unconfined discharge of water from the land to a receiving body of water. When this water contains materials that can potentially damage the receiving stream, the runoff is considered to be a source of pollutants.

permeability : The ease with which water and other fluids migrate through geological strata or landfill liners.

point source : An identifiable and confined discharge point for one or more water pollutants, such as a pipe, channel, vessel, or ditch.

porosity : The total volume of soil, rock, or other material that is occupied by pore spaces. A high porosity does not equate to a high permeability because the pore spaces may be poorly interconnected.

recharge : A hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plant roots, and is often expressed as a flux to the water table surface.

sorption : The physical or chemical linkage of substances, either by absorption or by adsorption.

total maximum daily load : The maximal quantity of a particular water pollutant that can be discharged into a water body without violating a water quality standard.

vadose zone : The area of the ground below the surface and above the region occupied by groundwater.

watershed : The area of land that drains into a lake or stream.