CHAPTER 2

THE HYDROLOGIC CYCLE, CLIMATE, AND WEATHER

THE PROPERTIES OF WATER
THE HYDROLOGIC CYCLE
CLIMATE AND WEATHER

All streams flow into the sea, yet the sea is never full. To the place the streams come from, there they return again.

Ecclesiastes 1

Ancient civilizations were curious about the world around them but had limited scientific knowledge regarding the natural processes of the oceans, land, and atmosphere. This led to some very interesting theories regarding the natural environment.

Thales (636–546 B.C), pronounced Thay'leez, is generally considered the founder of Greek science (see Figure 2.1). A merchant, seafarer, natural philosopher, and weather observer who lived in the Greek city of Miletus, Thales sought to determine the essence or substance of all matter. He theorized that everything in the universe originates and ends as water.

Through his observations of the weather and his time at sea, Thales reasoned that all things are made of water. Why else would the gods drop water from the heavens, allow it to flow into rivers and eventually to the oceans, and require that all living things consume water every day? It was an interesting philosophy that was shared by many in Greek society.

In many ways, Thales' philosophy of water described the hydrologic cycle. This natural cycle of precipitation, runoff, storage, and evaporation greatly affects all living things and alters the Earth's surface every day. The water in the hydrologic cycle changes the landscape, creates weather patterns, and provides life. One could still argue today that water is at the center of all things on Earth. For thousands of years, humans have tried to manipulate the hydrologic cycle through the construction of dams and canals to control the movement of water in the hydrologic cycle. Chapter 1 presented several examples of civilizations that developed elaborate urban and agricultural water delivery systems for drinking water, irrigation supply, and other uses. In this chapter, the role of the hydrologic cycle, climate, and weather will be considered as it relates to settlement patterns and water availability around the world. But first, we'll briefly discuss water and its unique characteristics.

FIG. 2.1 Bust of Thales of Miletus, one of the Seven Wise Men of ancient times.

THE PROPERTIES OF WATER

Water has remarkable properties. We all know that a molecule of water comprises two hydrogen atoms and one oxygen atom, but what allows water to turn into a solid and then back into a liquid? What allows insects to walk across its surface? And why does ice float, but most solid substances sink when placed in water?

Figure 2.2 shows that the two positively charged hydrogen atoms are attached to one side of a negatively charged oxygen atom. This causes a water molecule to have a positive charge on the side where the hydrogen atoms are attached, and a negative charge on the opposite side. Basic science classes taught us that opposite electrical charges attract, causing water molecules to attract to one other. The figure shows several water molecules attracted to each other with the positive and negative charges lining up together. The positive side of each water molecule aligns with the negative side of another molecule, and the negative side lines up with another molecule's positive side. This attraction of molecules is called **cohesion**. The hydrogen atoms have a strong bond with the oxygen atom, and a lesser bond with other hydrogen atoms. This weaker bond between the hydrogen atoms allows them to form, break, and reform with other water molecules. Gravity tends to deform the shape of water droplets; otherwise a drop of water would form a perfect sphere.

Water is called a "universal solvent," because it can dissolve more substances than any other liquid. Wherever water goes, it can be attracted to other substances, such as chemicals, minerals, and nutrients. This type of attraction with other molecules is called **adhesion**. Whether water moves through soils or passes through our bodies, water dissolves substances.[1] The positive and negative charges of a water molecule give it both cohesive and adhesive properties. The adhesive property of water causes it to be a universal solvent.

Water is unique because it can be found in solid, liquid, and gas forms at temperatures normally found on Earth. Earth is unique in that it has just the right range of temperatures and atmospheric pressures to allow this "triple point" for water. We know that water freezes at 32°F (0°C) and boils at 212°F (100°C) at sea level. However, at 14,000 feet (4267 m) above sea level, the temperature of water needs to reach

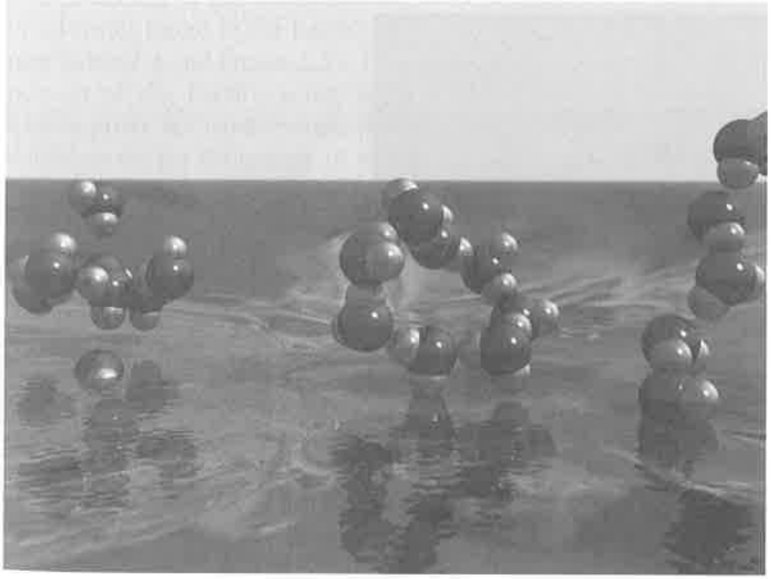

FIG. 2.2 These models show the potential structure of water molecules. An H_2O molecule is linked to four others based on many current scientific models (depicted on left). New results, however, suggest that most water molecules are linked strongly to only two others. This implies that liquid water molecules may be arranged in rings (depicted in the center) or chains (on the right), and are clustered together by additional, weaker hydrogen bonds. The oxygen atoms are shown as darker and the hydrogen atoms are lighter in these depictions of H_2O molecules.

only 186°F (86°C) to boil. Another unusual property is that solid water (ice) is less dense than liquid water, which is why ice floats. Most liquids contract when they get colder, and water behaves the same. However, water reaches its maximum density in liquid form at 39°F (4°C), just a few degrees above its freezing point. Water at this temperature stays at the surface as it begins to freeze, and then floats as a solid—a property shared by few other substances. If it didn't have this property, we would not have icebergs, ice cubes would sink, and lakes, ponds, rivers, and even oceans would eventually freeze from the bottom up. Instead, life as we know it can exist in cold weather because a floating skin of ice insulates life in the liquid water beneath the surface, allowing it to persist beneath a frozen surface.

Anyone who has lived in or visited the San Francisco Bay area has experienced the local moderation of climate. The city maintains a moderate year-round temperature, but just a few miles (km) inland, the climate has soaring summertime temperatures and freezing conditions in the wintertime. The reason for this contrast, as most residents know, is that San Francisco's climate is tempered by the waters of the Pacific Ocean.

SIDEBAR

Water can change from ice to a water vapor without first becoming a liquid. This process, called **sublimation**, occurs when water molecules in ice heat up enough to escape into the atmosphere as vapor, but not as liquid water. This can occur at low atmospheric pressures with temperatures below 32°F (0°C). You may have noticed snowbanks gradually shrinking even though temperatures remained below freezing for an extended period of time. The reason is sublimation.

Water has a high specific heat index, which means water can absorb a lot of heat before it gets hot. That is why water is often used in radiators to cool cars or buildings, and for transferring heat in thermal and chemical processes. Water's high specific heat index is another reason that the change in temperature between seasons is fairly gradual rather than sudden.[2] Atmospheric moisture is able to temper heat changes of the seasons.

A final unique property of water is its high surface tension—the measure of the strength of water's surface film. Water tends to bond together in droplets, creating a film that is thick enough to allow insects and small substances to bear their weight on a water surface (see Figure 2.3). Among common liquids, water's high

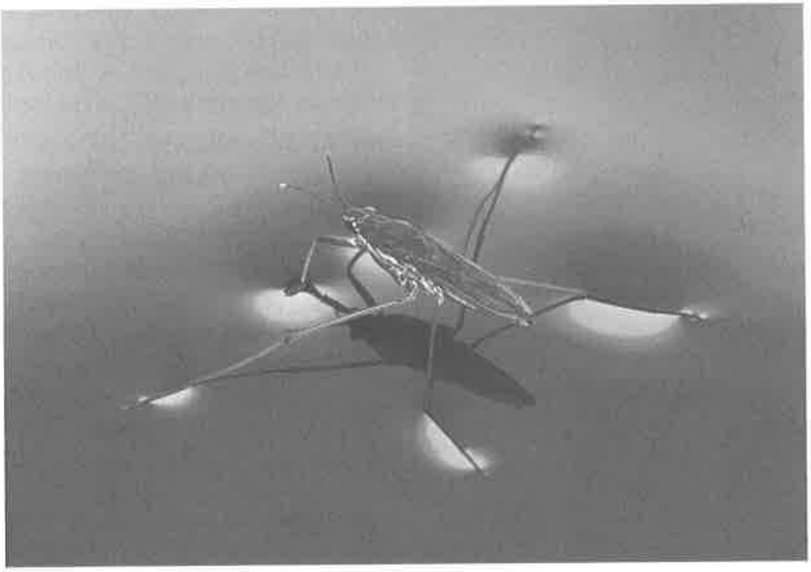

FIG. 2.3 Water striders are easy to identify by their long legs and lack of wings. They live and feed on the surfaces of ponds and other quiet water locations. A water strider relies on the surface tension of slow-moving or still water to move around and capture food. It can locate its prey by feeling vibrations on the water surface.

surface tension is surpassed only by that of mercury. This property allows capillary action to occur. In plants, this is the process of water droplets moving up through roots; in our bodies, blood moves through capillaries, tiny blood vessels, because of the adhesive properties of water.

SIDEBAR

Surface tension is essential for the transfer of energy from wind to water to create waves. Waves are necessary for rapid oxygen diffusion in lakes and seas.[3]

THE HYDROLOGIC CYCLE

The unique properties of water enable the movement of water between the land surface, groundwater, the oceans, and the atmosphere, a process called the **hydrologic cycle** (Figure 2.4). This natural process is driven by solar energy from the Sun. Moisture circulates from the Earth into the atmosphere through evaporation and then back to the Earth as precipitation. Water is not created or destroyed in this process but simply changes form and location.

The oceans of the world contain 97.5 percent of all water found in the Earth's hydrologic cycle (see Table 2.1 and Figure 2.5). The remaining 2.5 percent of the Earth's water is found either in frozen polar ice caps (where it may have been stored as ice for thousands of years), as groundwater beneath the land surface, or in rivers, lakes, ponds, wetlands, or moisture in the atmosphere. Table 2.1 shows the breakdown of these water storage locations.

The hydrologic cycle contains five key components:

1. Precipitation
2. Runoff
3. Surface and Groundwater Storage
4. Evaporation/Transpiration
5. Condensation

PRECIPITATION

Precipitation occurs when atmospheric moisture becomes too great to remain suspended in clouds. Under proper conditions, small, weakly linked molecules of water form droplets. These undergo a further process of coalescence, or joining together, and fall in the form of rain, snow, sleet, hail, or **virga** (rain that evaporates before reaching the ground). Once it reaches the Earth's surface, precipitation can become surface water runoff, surface water storage, glacial ice, water for plants, groundwater, or salt water in the oceans, or it may evaporate and return immediately to the atmosphere.

Ocean evaporation provides approximately 90 percent of the Earth's precipitation. However, living near an ocean does not necessarily imply increased rainfall. Southern California and the island of Aruba, near Venezuela, are examples of relatively dry regions adjacent to an ocean or sea. Aruba receives only 17 inches (430 mm) of precipitation per year and relies on reservoir storage and desalination of salt water from the Caribbean Sea for its water supply. San Diego, located along the shores of the Pacific Ocean in southern California, has an average annual precipitation of only 10 inches (250 mm) and receives very limited rainfall during the summer. The reasons for such natural climatic phenomena will be discussed later in this chapter.

Table 2.2 presents a wide range of average annual precipitation quantities when comparing western U.S. cities such as Phoenix, Denver, and Los Angeles, to eastern cities such as Atlanta and Bangor. However, average annual participation in Portland, Oregon, is an anomaly when compared to Los Angeles because it receives over 300 percent more average annual participation. Why? (Check your hypothesis when climate and weather are discussed later in this chapter.)

Figure 2.6 and Table 2.3 present average annual precipitation totals from around the world. Notice the low rainfall amounts (less than 11 in., or 280 mm) for Cairo, Ahmadi, Riyadh, Damascus, Tehran, and Amman. The Tigris, Euphrates,

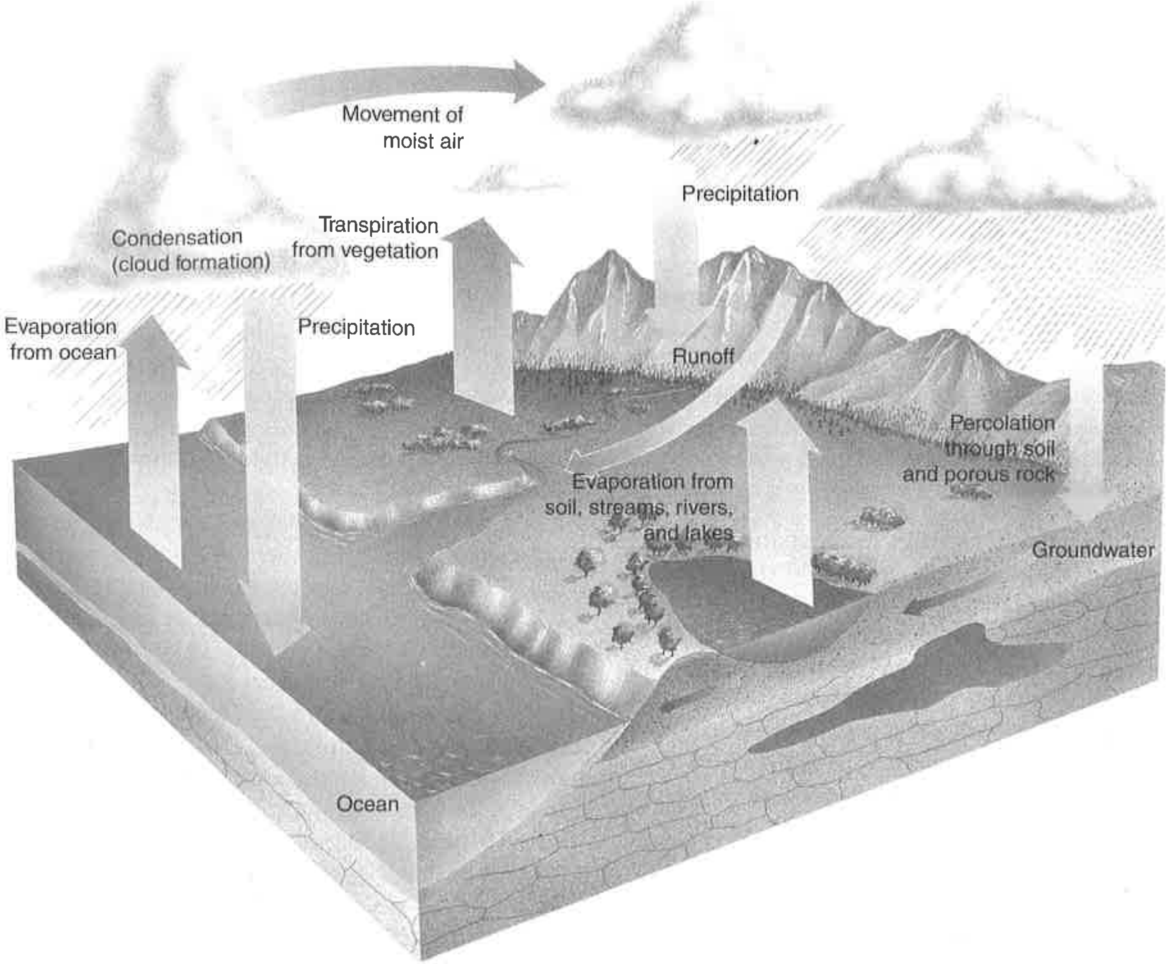

FIG. 2.4 This simplified diagram of the hydrologic cycle shows the pilgrimage of water as it makes its way from the Earth's surface to the atmosphere, back to the land surface as precipitation, into rivers, lakes, soils or aquifers, or the ocean, and back to the atmosphere. All aspects of the cycle occur simultaneously, making it a remarkably simple yet complex subject of study. The hydrologic cycle—powered by the energy of the sun—has continued on Earth for millions of years.

TABLE 2.1 Total Water Supplies in the Hydrologic Cycle

Location of Storage	Total	Percent of Freshwater	Estimated Age of Water
Total water on Earth	100.0		Variable
Seawater	97.5		4000 yr. (approx.)
Total freshwater	2.5	100.0	Variable
Ice caps and glaciers		74.0	10–10,000 yr.
Groundwater		25.6	2 wk.–10,000 yr.
Lakes, rivers, soil moisture, and atmosphere		0.4	10 days–10 yr. (approx.)

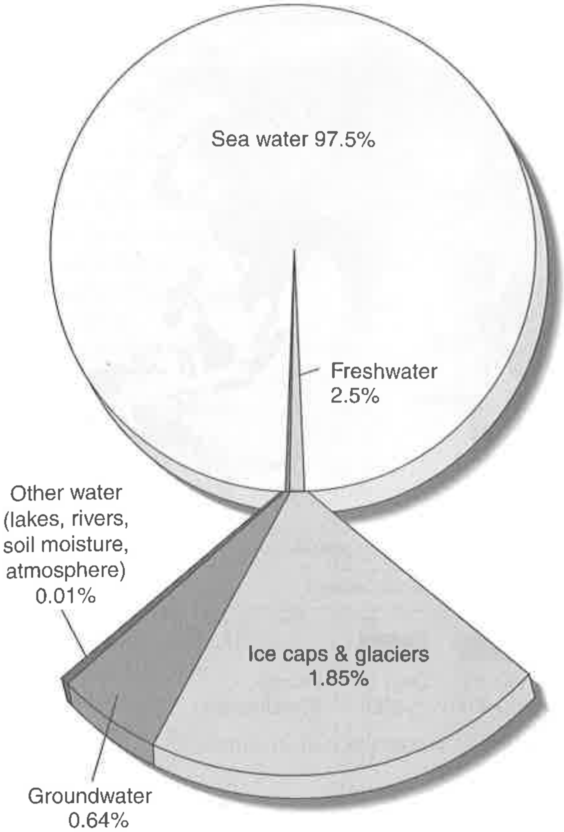

FIG. 2.5 Distribution of the world's total water supply in the hydrologic cycle. Less than 1 percent is available to humans, since most water is seawater, frozen, or inaccessible in soil moisture or the atmosphere.

TABLE 2.2 Average Annual Precipitation for Selected U.S. Cities

City	Amount	
	Inches	Millimeters
Phoenix, Arizona	7.6	193
El Paso, Texas	8.6	218
Los Angeles, California	11.9	302
Denver, Colorado	15.4	391
Salt Lake City, Utah	15.6	396
Fargo, North Dakota	19.6	498
Dallas, Texas	35.0	889
Chicago, Illinois	35.8	909
Portland, Oregon	36.3	922
Columbus, Ohio	37.8	960
Seattle, Washington	38.1	968
Kansas City, Missouri	38.2	970
Bangor, Maine	40.5	1029
New York, New York	41.5	1054
Atlanta, Georgia	49.8	1265
Memphis, Tennessee	52.7	1339
Miami, Florida	59.0	1499

Source: National Climate Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, North Carolina, http://www.ncdc.noaa.gov/ol/climate/globalextremes.htm, September 2001.

and Nile rivers flow through these **arid** regions (areas that receive less than 10 in., or 250 mm, of average annual precipitation) and provided the irrigation water the early civilizations needed to survive. Without this supplemental water, crops such as wheat would have died, since grains require approximately 15 inches (380 mm) of moisture during the growing season. The precipitation component of the hydrologic cycle (or the lack of it) played a major role in settlement patterns, water use, and the construction of irrigation projects in this desert region.

Tables 2.4 and 2.5 show the erratic nature of the hydrologic cycle. Notice that the island of Hawaii has both the high and low precipitation extreme records. Elevation is the key reason to Hawaii's extremely variable precipitation and will be explained later in this chapter.

Measuring Precipitation Precipitation measurement is a very important tool in understanding the amount of water available for human and plant use. A variety of methods are available to obtain data on the amount, location, and intensity of precipitation events. This information allows growers, municipal water providers, crop scientists, forest managers, and others to adjust water use patterns.

Simple rain gages have been used in India, China, and Korea for more than a thousand years (Figure 2.7). In 300 B.C. India used rain gages to determine tax collections. Periods of high rainfall meant good crops and higher taxes, whereas low rainfall meant poor crops and a tax break from the government. The rain buckets

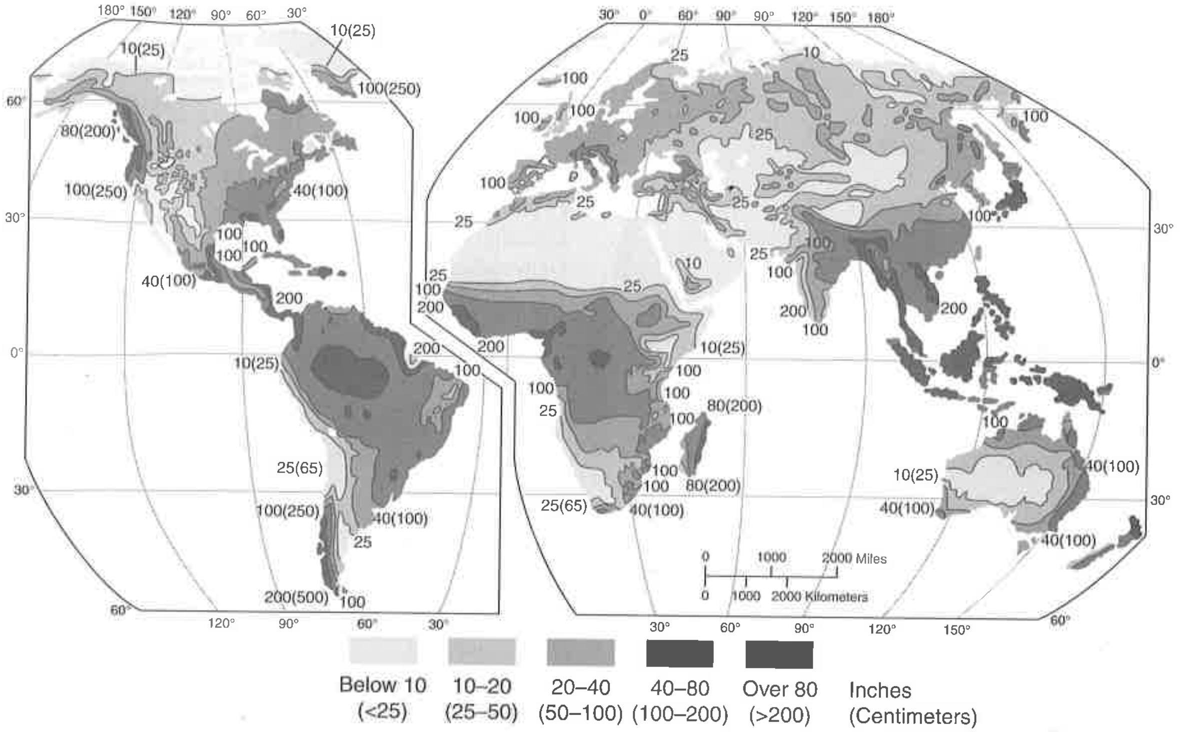

FIG. 2.6 Distribution of average annual precipitation around the world. (Numbers in parenthesis are in centimeters.)

and precipitation tubes used in ancient times were not much different from some of the instruments used today. Modern measuring devices range from simple plastic and glass tubes available at hardware stores to elaborate "weigh and tip" bucket gages used by the U.S. National Weather Service (NWS). Accurate precipitation measurement requires the placement of rain gages away from trees, buildings, and other features that could interfere with rainfall. Networks of rain gages can be distributed across a wide area to determine the quantity of rainfall over a large geographic region.

Doppler radar provides a sophisticated and accurate method of precipitation measurement. The name is derived from the Doppler effect, which was first mathematically described in 1842 by Christian Doppler (1803–1853), an Austrian physicist. Doppler studied the apparent change in sound frequencies as an object, such as a train whistle, approached and then passed a stationary person. His concept of frequency and sound movement is used in Doppler radar to estimate rainfall amounts based on the intensity of radar echoes.[4] This modern technology sends out continual electromagnetic waves that bounce off suspended water droplets in the air and return as an electronic signature back to a computer. The distribution of droplets provides data on storm intensity and precipitation amounts. Scientists are now using Doppler radar data from previous storms to estimate historic precipitation amounts. This information provides spatial, gridded, historic precipitation estimates that are not available with rain gage monitoring networks.

In some regions of the world, snow depth measurements are a very important aspect of monitoring precipitation. Snowpack is measured in mountainous areas, or in drifts or blankets of snow at lower elevations, to determine the amount of liquid water available. In some areas,

TABLE 2.3 Average Annual Precipitation for Selected World Cities

City	Amount Inches	 Millimeters
Cairo, Egypt	1.0	25
Ahmadi, Kuwait	3.9	99
Riyadh, Saudi Arabia	4.4	112
Damascus, Syria	7.4	188
McMurdo, Antarctica	8.0	203
Tehran, Iran	9.5	241
Amman, Jordan	10.7	272
Madrid, Spain	17.3	439
Prague, Czech Republic	18.9	480
St. Petersburg, Russia	21.2	538
London, Great Britain	23.2	589
Paris, France	23.9	607
Beijing, China	25.0	635
Nairobi, Kenya	29.2	759
Rome, Italy	31.2	792
Reykjavik, Iceland	32.2	818
Johannesburg, South Africa	33.3	846
Perth, Australia	34.1	866
Montreal, Quebec	40.8	1036
Rio de Janeiro, Brazil	43.4	1102
Brazzaville, Congo	54.0	1372
Tokyo, Japan	60.0	1524
Yaounde, Cameroon	62.9	1598
Jakarta, Indonesia	71.7	1821

Source: National Climate Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, North Carolina, http://www.ncdc.noaa.gov/ol/climate/globalextremes.html, September 2001.

snowmelt will provide water supplies for farms and communities at lower elevations during the warmer late spring and summer months.

The U.S. National Weather Service and other agencies around the world monitor snowpack. Measurements are typically obtained during winter and early spring months to determine the depth and water content of snow at various locations. A **snow tube** is used to collect a vertical snow sample from the top of the snow down to the land surface. The metal tube has a sharp edge that cuts through frozen layers of ice and snow when rotated and pushed downward. The depth of snow is measured, and then the tube and snow contents are weighed to determine water content.

Snow cores are taken along an established line, called a **snow course,** to take into account variations in snow depth and characteristics. The **water equivalent** is the amount of liquid that will result from the melted snow. This quantity varies based on snow density, water volume, and snow depth. Monthly reports are often prepared to provide water users and managers with current snow depth and water-equivalent data. These data are usually compared to previous years and long-term averages.

Snow pillows are also used to determine the water content of snow. The pillows are made of stainless steel and are rectangular with sides of approximately 4 feet by 5 feet (120 cm by 150 cm)

TABLE 2.4 Low Annual Precipitation Extremes around the World

Location	Amount		Elevation		
	Inches	Millimeters	Feet	Meters	Years of Record
Arica, Chile	0.03	1	95	29	59
Wadi Halfa, Sudan	0.1	3	410	125	39
Amundsen-Scott South Pole Station, Antarctica	0.8	20	9186	2800	10
Batagues, Mexico	1.2	30	16	5	14
Aden, Yemen	1.8	46	22	7	50
Mulka, South Australia	4.05	103	160	49	42
Astrakhan, Russia	6.4	163	45	14	25
Puako, Hawaii, United States	8.93	226	5	5	13

Source: National Climate Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, North Carolina, http://www.ncdc.noaa.gov/oa/climate/globalextremes.html, December 2007.

TABLE 2.5 High Annual Precipitation Extremes around the World

Location	Amount		Elevation		Years of Record
	Inches	Millimeters	Feet	Meters	
Lloro, Colombia	523.6[a]	13,299	520	158	29
Mawsynram, India	467.4	11,872	4597	1401	38
Mt. Waialeale, Kauai, Hawaii, United States	460.0	11,684	5148	1569	30
Debundscha, Cameroon	405.0	10,287	30	9	32
Quibdo, Colombia	354.0	8992	120	37	16
Bellenden Ker, Queensland, Australia	340.0	8636	5102	1555	9
Henderson Lake, British Columbia, Canada	256.0	6502	12	4	14
Crkvica, Montenegro	183.0	4648	3337	1017	121

[a] Estimate.

Source: National Climate Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, North Carolina, http://www.ncdc.noaa.gov/oa/climate/globalextremes.html, December 2007.

and a thickness of approximately 1 foot (30 cm). As snow accumulates, pressure on antifreeze fluid inside the pillow increases. This increase in pressure is electronically recorded and transmitted via satellite to monitoring stations at lower elevations. This type of snow-monitoring system eliminates the need for scientists to hike into remote mountainous regions during the winter (see Figure 2.8).

FIG. 2.7 The world's oldest surviving rain gages were invented in the 15th century in present-day Korea, and were typically placed near government facilities in provinces and cantons of the country to monitor precipitation for planning purposes. The gage in this photo is called Chuk-u-gi, from the early Joseon Dynasty in A.D. 1441, and is the oldest in the world. Although some rainfall records in Korea have been lost or destroyed, a few locations have data that go back over 250 years—which are extremely valuable when investigating climate change in the region.

RUNOFF

Runoff is the amount of water that flows across the land surface after a storm event. Chapter 1 described the efforts of the ancient Anasazi Indians to capture runoff during rainstorms by diverting and channeling water into small lakes or onto fields for irrigation. Runoff played an extremely important role in the Anasazi's ability to live in the harsh, arid climate of southwest Colorado.

Climate, terrain, precipitation intensity, and volume play a large role in surface water runoff. The Amazon River Basin in South America has tremendous runoff volume due to high precipitation rates, high humidity, and a massive drainage area. The Los Angeles Basin in southern California also has high runoff volume, but generally only for short time durations due to infrequent but intense rainfall events, hard and impervious soils, and extensive developed areas of concrete and rooftops. In contrast to these examples, the Sandhills of

FIG. 2.8 Snow pillow station at a mountain station in Utah. An interesting website on snow pillow data, entitled "Seasonal Automatic Snow Pillow (ASP) Plots for B.C.," can be found at http://www.env.gov.bc.ca/rfc/river_forecast/snowp.htm. The website is operated by the Water Stewardship Division of the Ministry of Environment, Government of British Columbia, Canada.

central Nebraska generally have low runoff volumes owing to lush ground cover of native grasses, gently rolling terrain, and very porous (sandy) soils that allow runoff to seep underground (see Figure 2.9).

SID[illegible] [illegible]

Water managers at the Natural Resources Conservation Service in Denver (an agency within the U.S. Department of Agriculture) monitor snowpack monthly in all watersheds of Colorado and other western states to produce monthly reports. These data are used to predict stream flows during dry summer months and are available to municipal water managers, irrigators, and other water users for planning purposes. Go to http://www.wcc.nrcs.usda.gov/wsf for more information.

Land use has a significant effect on surface water runoff. Barren land surfaces hinder water seepage into the soil and cause runoff to move rapidly downhill. Dense vegetative cover slows surface water flow and allows increased seepage rates. Urban areas with paved streets and parking lots, sidewalks, and roof tops prevent seepage and increase runoff. Areas downstream of urban areas often experience increased stream flow after major storm events. Measurement of runoff will be discussed in Chapter 3, and relationships between runoff and groundwater will be discussed in Chapter 4.

SURFACE AND GROUNDWATER STORAGE

Lakes and Reservoirs Lakes and reservoirs are important components of the hydrologic cycle. **Lakes** are large bodies of inland water often formed by glacial activity or surface water runoff, whereas **reservoirs** are either natural or artificial water bodies used to store, regulate, and control water. Both lakes and reservoirs serve as collection points for storage of surface water runoff and groundwater seepage, lose water to evaporation, and can replenish the flow in streams.

Lakes and reservoirs can be created by landslides, tectonism (movement of geologic formations), glaciation, river action, animal activity (beavers), meteorite impact, volcanism, and human activity (construction of dams). Two of the largest and deepest lakes in the world were created by tectonism. Lake Baikal in Russia is the largest and deepest freshwater lake on Earth, with a depth of 5250 feet (1600 m). It contains as much freshwater as all of the Great Lakes of North

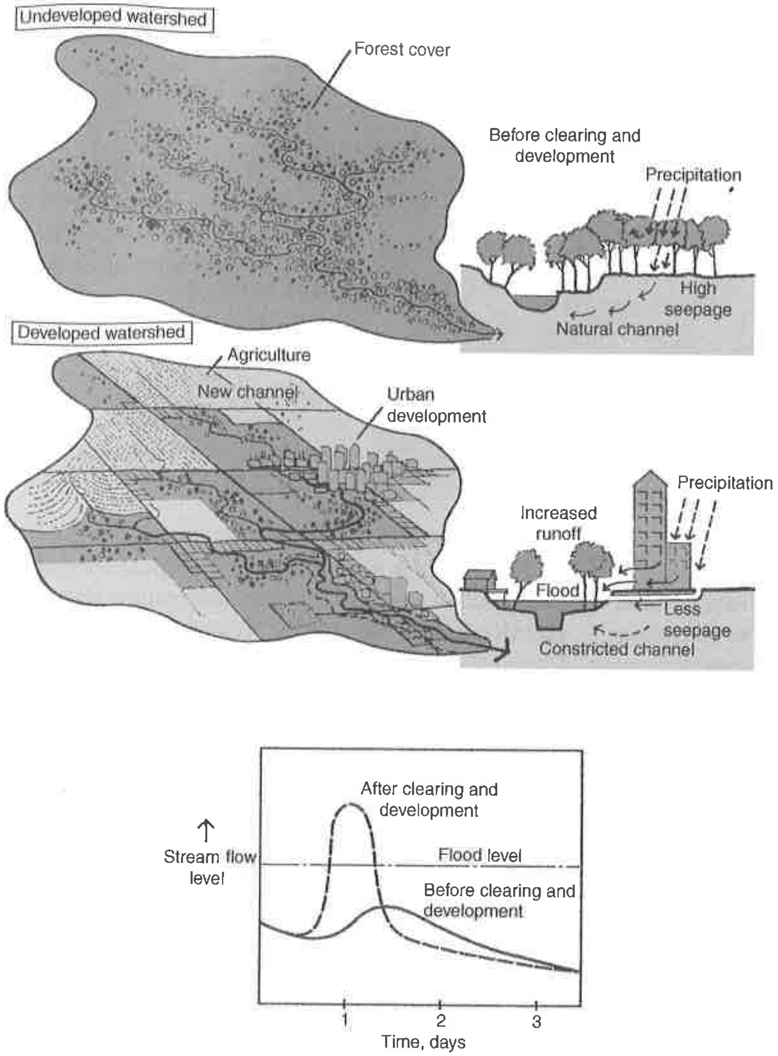

FIG. 2.9 Surface water runoff and stream flow can change dramatically when land use patterns change from undeveloped vegetation to agriculture or urban development. The graph shows a corresponding change in stream flow from a storm event. Note the tremendous change in stream flow levels before and after clearing and development. What problems will this cause?

America combined—roughly 20 percent of the world's total surface freshwater. Lake Tanganyika, in eastern Africa and bordered by Zambia, Tanzania, Burundi, and the Democratic Republic of Congo (Zaire), is the longest lake in the world (416 mi, or 670 km) and the second deepest at 4823 feet (1470 m). Lake Tahoe, along the border between California and Nevada, was shaped and landscaped by scouring glaciers. It is the second deepest lake in the United States and the tenth deepest in the world, with a maximum depth measured at 1645 feet (501 m). Crater Lake in Oregon, the deepest lake in the United States, has a maximum depth of 1932 feet (589 m) and was created by an ancient volcano named Mount Mazama.

Many lakes in the Northern Hemisphere were created by glacial ice that moved southward out of Canada during the Ice Age and then melted and receded as global warming occurred. The Finger

Lakes in upstate New York, Great Slave Lake in the Northwest Territories of Canada, and the Great Lakes of North America were created by this type of glacial action.

SIDEBAR

According to the Canadian Hydrographic Service, Department of Fisheries and Oceans, a century of water level records of the Great Lakes indicate no regular, predictable cycle. The maximum variation of lake levels ranges from 3.9 feet (1 m) in Lake Superior to over 5.9 feet (2 m) in the other lakes.[5]

Lakes and reservoirs rely on precipitation, snowmelt, and in some cases, groundwater infiltration and glacial melt as sources of water. Water stored in lakes is lost through evaporation, groundwater recharge, and outflow. Many lakes and reservoirs are closely monitored by water managers to determine water storage volumes. Chapter 3 will discuss the natural functions of lakes, while Chapter 7 will describe the construction of dams to create water storage reservoirs.

CASE STUDIES

Following are two brief examples of natural and human-caused events that have significantly altered water levels in lakes around the world.

Example: Great Salt Lake of Utah

Great Salt Lake is a terminal lake, with no outlet river extending to an ocean. The lake is shallow for its size—about 70 miles (113 km) long and 30 miles (48 km) wide, but only approximately 40 feet (12 m) deep. The lake bottom is so gently sloped that any increase in inflow causes a broad surface area to be inundated with water.

In 1982, rainy weather brought the highest water levels in Great Salt Lake in recorded history. Since it has no outlet, water levels in the lake responded dramatically to increased surface water runoff and reached record levels in June 1986 and March–April 1987. Lake levels increased 12 feet (4 m), causing floodwaters to inundate Interstate Highway 80 and parts of Salt Lake City on the south side of the lake.[6]

In response, the State of Utah implemented the West Desert Pumping Project to lower water levels in Great Salt Lake. Three large pumps were installed and pumped water from the lake onto the Bonneville Salt Flats to the west, creating the Newfoundland Evaporation Basin. The first pump was turned on in April 1987 and ran until June 1989 (see Figure 2.10). The combination of pumping, evaporation, and reduced inflow caused lake levels to drop, with about 2 feet (1 m) of the decline due to pumping. The pumps were operated for two years at a cost of over $60 million.[7]

During the late 1800s, to coax settlement in the West, American pioneers often heard the phrase "Rain follows the plow." Land speculators argued that crop production would generate more evaporation and transpiration, and so would cause precipitation to increase. Scientists noted that water levels in Great Salt Lake rose after Mormon settlers began irrigating nearby lands. Others believed that enlarged water surfaces, created by the construction of reservoirs, would also increase evaporation and precipitation. Both claims were overblown and misleading, causing great human misery when drier times prevailed.

Example: The Aral Sea of Uzbekistan

The Aral Sea is dying. Once-prosperous fishing villages along this Central Asia water body are now 60 miles (96 km) from the shore, with water so salty that all fish have died. It has been estimated that the entire sea will disappear around 2020.

In about 1965, officials of the former Soviet Union tapped this large body of water (the fourth largest lake in the world at the time) for irrigation. The sea covered 26,255 square miles (68,000 km^2) and had an average depth of 52 feet (16 m). Fish production was tremendous, but Soviet officials wanted to develop irrigation to

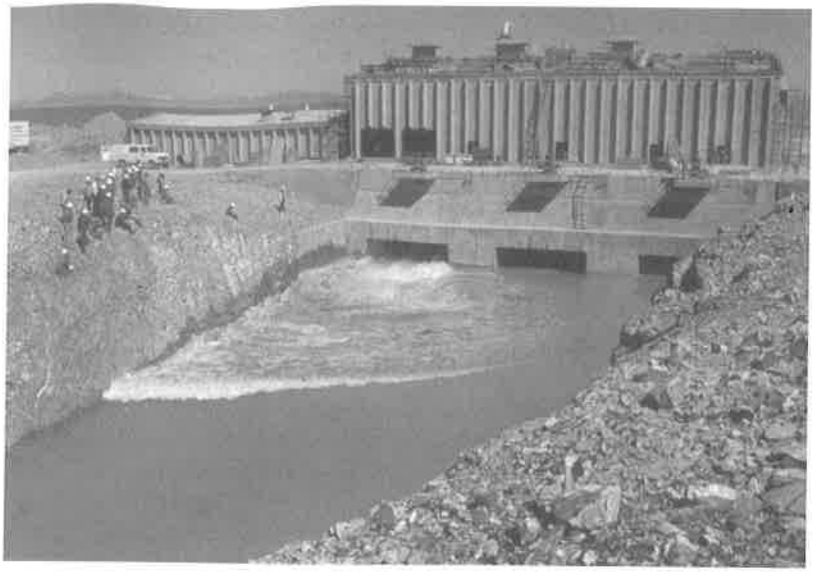

FIG. 2.10 This photo was taken during the first pump test of the Great Salt Lake West Desert Pump Plant in 1987. Great Salt Lake is the largest lake in the Western Hemisphere without an outlet to the sea, and is a remnant of ancient Lake Bonneville. Changing climatic conditions are causing long-term fluctuations in lake levels in Great Salt Lake, located just northwest of Salt Lake City, Utah.

boost the regional economy. Although planners were aware that the size of the water body would shrink, no one was prepared for the magnitude of change that resulted (Figure 2.11).

Today, the Aral Sea is less than 50 percent of its previous size and contains less than 25 percent of its volume in 1960. The resulting concentration of salts and chemicals has killed all plant and animal life and has destroyed a productive fishing industry, with tens of thousands of people abandoning their fishing livelihoods. A dry, desert landscape has replaced the retreated water surface, and dust storms, warmer local temperatures, and increased winds are common.

The World Bank has launched a program to develop drinking-water supplies and to restore some plant and animal life in the area. However, 95 percent of the surface runoff that historically entered the Aral Sea is now diverted for other uses. The local climate of this region has been moderated with hotter, shorter summers and longer, colder winters. Wind-scattered dust from the dry lake bed carries for great distances and has increased respiratory illnesses and other diseases.

Will the Aral Sea ever return to its previous condition? Unfortunately, many experts predict that will not happen. Even so, the independent republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan have signed cooperative agreements to attempt to develop a regional water management system to return some water to the Aral Sea.[8]

Wetlands Wetlands play a very important role in the storage of water within the hydrologic cycle. A **wetland** can be described as an area of standing water, usually shallow, that contains cattails or other hydric (water-loving) plants. Wetland scientists and the U.S. Fish & Wildlife Service adopted a formal definition of wetlands in 1979 after several years of review. In a report titled *Classification of Wetlands and Deepwater Habitats of the United States* (Cowardin et al., U.S. Department of the Interior, Fish & Wildlife Service, Washington, D.C., 1979) wetlands are defined as follows:

> *. . . lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water . . . . Wetlands must have one or more of the following three attributes: (1) at least periodically, the land*

FIG. 2.11 The Aral Sea is located between Kazakhstan and Uzbekistan, both former Soviet Socialist Republics. During the communist period, large-scale irrigation projects were developed that dramatically reduced flows into this inland sea. Fishing villages that were once located on the shores of the Aral Sea are now 60 to 90 miles (96 to 144 km) from water. In addition, the increased concentration of pollutants in the Aral Sea has totally destroyed the fishing industry, and many fishing vessels were simply abandoned.

supports predominantly hydrophytes (plants that have adapted to life in soils that are often flooded or saturated with water); (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

SIDEBAR

In 1971, the Ramsar Convention on Wetlands (named after its meeting location in Ramsar, Iran) adopted as part of its text the rationale for protecting sites was the "fundamental ecological functions of wetlands as regulators of water regimes." For the hydrologic cycle, these functions include:

- Water storage: Surface water storage, flow regulation, flood mitigation, groundwater recharge, and groundwater discharge
- Water quality: Water purification, nutrient retention, sediment retention, and retention of pollutants
- Local climate regulation: Stabilization of the local climate, regulation of rainfall and temperature, and reduction of evapotranspiration

The Ramsar Convention document goes on to say that freshwater wetlands are a fundamental and manageable component of the global hydrologic cycle.[9]

Wetlands are often found along rivers, lakes, deltas, estuaries, and swamps. These marshy areas provide excellent habitat for wildlife, can induce groundwater recharge, reduce erosion during floods, and provide temporary and permanent storage areas for surface water runoff. In addition, a wetland can improve water quality. Wetlands will be discussed in more detail in Chapter 12.

Groundwater Groundwater storage is another important component of the hydrologic cycle. Porous soils allow surface water to seep downward into the soil and underlying geologic material under the force of gravity. Precipitation is the principal method for replenishing groundwater. Some moisture movement below the land surface is controlled by capillary pressure and hydraulic conductivity (discussed in Chapter 4).

Groundwater can be found beneath the land surface in sand and gravel, rocks, fine clay material, and cracks in large rocks. Surface water can also become groundwater through seepage from streams, lakes, wetlands, and salt water. Groundwater moves under the force of gravity and through capillary action, through geologic material to lower elevations until it reaches an underground barrier such as clay or rock. Groundwater can eventually reach the land surface at a lower elevation as a spring, or it can infiltrate into a stream, lake, wetland, or ocean.

Increasingly, the interaction of surface and groundwater is becoming a greater issue in regions of the world where groundwater pumping affects stream flow. In Colorado, for example, thousands of wells that utilize groundwater (for irrigation, livestock watering, and domestic water supply) were shut off permanently because of declining surface water supplies in the South Platte River. The connection between groundwater pumping and stream flow is becoming a greater problem as limited freshwater supplies are overused. Groundwater properties, aquifers, water tables, movement, and effects on stream flow will be discussed in Chapter 4.

EVAPORATION

Evaporation is the process of liquid water converting into vapor, through wind action and solar radiation, and then returning to the atmosphere. Evaporation occurs from open bodies of water, such as lakes, rivers, and the ocean, and from land surfaces. Evaporation rates are extremely important to determine water availability or water loss rates in a region. These rates can be measured by filling special pans with water and then recording daily loss rates.

The English astronomer-mathematician Sir Edmond Halley (1656–1742) conducted experiments in about 1701 to estimate evaporation from the Mediterranean Sea. He set out several small pans filled with water during hot summer days and calculated the amount of water that evaporated from the Mediterranean in a single day. He then estimated the daily flow of freshwater from contributing rivers and determined a net loss of water to the system. Evaporation, Halley theorized, would lead the Mediterranean Sea to become saltier, since the net water lost from the Mediterranean exceeded freshwater inflow.[10]

Future research proved Halley correct in his theory that the deeper Mediterranean waters were saltier than the adjacent Atlantic Ocean. Halley continued his work with the hydrologic cycle and evaporation; he also later discovered the comet that carries his name today.

The small pans that Halley used to estimate evaporation in the Mediterranean are very similar to devices used today. The U.S. National Weather Service and other scientific agencies around the world use **Class A Evaporation Pans** to determine evaporation rates. These galvanized steel pans have a diameter of 48 inches (120 cm) and a depth of 10 inches (25 cm). Generally, a pan is filled to a depth of 8 inches (20 cm) and is refilled whenever the water level drops to 7 inches (18 cm). Water levels in the pan are recorded daily. Errors in measurement can occur if an animal drinks water from the pan, if wind causes water to splash out, or if heating of the metal increases evaporation. The error in evaporation readings caused by excess energy conducted through the walls of the pans can be corrected by using a **pan coefficient.** This adjusting factor will lower the pan evaporation rate to more closely reflect actual values; it varies based on the average temperature and elevation of a region.

Evaporation from reservoirs can be significant, particularly in arid regions such as western portions of the United States (see Figure 2.12), northern Mexico, Australia, and the Middle East. Along the Front Range of Colorado, water levels in lakes can drop between 2 and 4 feet (about 1 m) every year. In Nevada, Lake Mead loses over 3 percent of its stored water annually to evaporation. The U.S. Geological Survey has calculated that 70 percent of Georgia's 50 inches (1270 mm) of annual precipitation returns directly to the atmosphere through evaporation. Of the remaining 30 percent, approximately 20 percent will become surface runoff, and 10 percent will seep into the soil and become Georgia groundwater.[11]

In the 1940s, H. L. Penman worked for the British Army and developed the **Penman equation** to estimate evaporation rates from plants and soil.[12] This mathematical formula

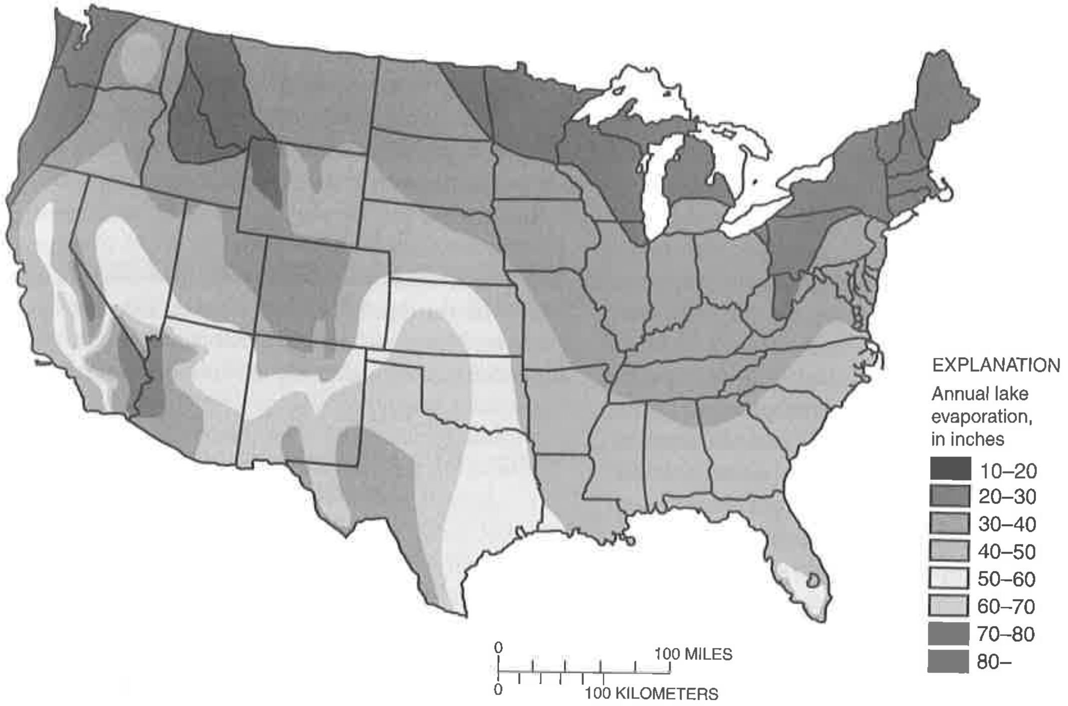

FIG. 2.12 Annual lake evaporation. Apart from precipitation, evaporation is probably the most significant component of the hydrologic budget. Evaporation varies regionally and seasonally; during a drought it varies according to temperature, weather, and wind conditions. This map shows that the desert southwest region of the U.S. loses over 80 inches (2000 mm) of water annually from lake surfaces through evaporation. This is significant for these same locations which receive less than 10 inches (250 mm) of precipitation annually.

includes the effects of sunshine duration, solar radiation, wind speed, temperature, and vapor pressures on evaporation rates. However, many of the data inputs necessary for this equation are not generally gathered at monitoring sites and must be estimated by researchers. Modified several times since its creation, this formula is now called the modified Penman equation.

Sublimation, an important part of the evaporation process described in the first section of this chapter, allows snow or ice to change directly into water vapor, or vice versa, without going through the normal melting process. Snow and ice sublimate (convert between a solid and gaseous state) during the winter and reduce available water supplies for downstream water users. Wind, temperature, and elevation variations can cause the loss of up to 52 percent of available water supply in snowpack in any given season due to sublimation.[13]

Transpiration occurs when water molecules exit living plant tissue (especially leaves, but also roots, flowers, and stems) and enter the atmosphere. (Transpiration also occurs from animals, but on a much smaller scale than in plants.) In areas of abundant rainfall, transpiration from plants is fairly constant, with variations occurring primarily in the length of each plant's growing season. However, transpiration in dry areas varies greatly by root depth. Shallow-rooted plants often wither and die owing to a lack of moisture, but deep-rooted plants, such as alfalfa *(Mendicago sativa)* or cottonwood trees *(Populus deltoids),* will continue to transpire water because of roots that can tap into deeper groundwater supplies. Deep-rooted, water-loving plants are called **phreatophytes** and are often found along river corridors or in areas where the depth to groundwater is not excessive.

Evapotranspiration (ET) includes all evaporation from water and land surfaces, as well as transpiration from plants. ET rates vary greatly throughout the year and are primarily dependent on temperature, wind, and atmospheric moisture conditions. C. Warren Thornthwaite (1899–1963) introduced the concept of **potential evapotranspiration** in the late 1940s.[14] Potential ET is the amount of water in a plant that will be lost if there is never a water deficiency in the soil for use by the plant. This theory recognizes that a plant can consume only so much water during a complete growing season. The application of additional water to a plant, through precipitation or irrigation, cannot be utilized by a plant and will simply percolate downward past its roots. Thornthwaite's concept was very important because it developed the maximum water requirements of various crops. The concept of potential evapotranspiration is still widely used around the world.

A CLOSER LOOK

Many scholars consider C. Warren Thornthwaite the most outstanding American climatologist of the 20th century. His research into potential evapotranspiration and the water balance model (which compares water need with water supply) was first published in 1948. Previously, Thornthwaite was a geography professor at the University of Oklahoma; later he became chief of the Climatic and Physiographic Division of the Soil Conservation Service in the U.S. Department of Agriculture.

In 1946, he joined Seabrook Farms in New Jersey as an irrigation consultant. While at Seabrook, the U.S. Army and Air Force entered into a contract to have Thornthwaite conduct experiments on evapotranspiration. The military was interested in his research because it believed Professor Thornthwaite could provide valuable weather forecasting. This information could influence vehicular movement on unpaved surfaces, the prediction of fog and wind conditions, and chemical warfare forecasting.[15]

The **Blaney-Criddle method** was developed by the U.S. Department of Agriculture in the 1950s and is also used to estimate evapotranspiration (ET) rates. This mathematical method uses crop ET rates based on differing water needs during the growing season as plant size increases.

Lysimeters can be used to directly measure the evapotranspiration rates of various types of vegetation. A soil-filled tank is buried at ground level and filled with the type of soil and vegetation to be tested, such as bluegrass or corn. All water inputs and outputs are weighed using the following equation:

$$ET = Si - Sf + P + I - D$$

where ET = evapotranspiration for the test period
Si = volume of soil moisture at the beginning of the experiment
Sf = volume of soil moisture at the end of the experiment
P = amount of precipitation entering the lysimeter
I = amount of irrigation water entering the lysimeter
D = amount of moisture drained from the soil

In some locations, satellite imagery can be used to determine the amount of water consumed by irrigated crops based on color and heat radiated by various crops. ET rates can be computed based on this infrared photography from space.

Consumptive use (CU) is the amount of water transpired and retained within a plant or animal. For example, the consumptive use of corn includes the amount of water transpired during a growing season plus the volume of water stored in the corn stalk and ears. The following equation computes the consumptive use:

$$CU = ET + Sc$$

where CU = consumptive use for a growing season
ET = evapotranspiration rate for the entire growing season
Sc = amount of water stored in the plant tissue

Consumptive use is an extremely important measurement of water use. Since consumptive use water is lost to the local surface and groundwater system, water managers and engineers often go to great lengths to determine the precise consumptive use quantities of various crops and animals.

SIDEBAR

Australian farmers are measuring soil moisture in their paddocks (closed areas used to pasture animals) with data provided by satellite. The University of Melbourne (located in the state of Victoria in southeast Australia), NASA, and the European Space Agency joined forces in 2007 on an international experiment to test and enhance satellite technology. Farmers can now predict soil moisture and crop yields for weeks in advance. Soil moisture is measured 2 inches (5 cm) below the land surface by the satellite, but a small aircraft fitted with similar satellite equipment can measure soil moisture as deep as 3 feet (1 m) underground. This effort led to the first dedicated soil moisture satellite, called the SMOS (for Soil Moisture and Ocean Salinity), which was launched in 2008, to assist farmers and water managers around the world in the future.

CONDENSATION

Condensation is the cooling of water vapor until it becomes a liquid. This process begins when water vapor in the atmosphere rises in the air and cools. As this occurs, the water vapor undergoes a change of state into liquid or ice. If other atmospheric conditions are present, this process can form clouds at higher elevations, or fog if close to the Earth's surface. As the droplets collide, they merge and form larger droplets. This process is noticeable on plants as they collect dew in the morning, as well as on a can of soda when you take it out of a refrigerator.

A CLOSER LOOK

In 1992, fog water flowed out of local water taps in Chungungo, Chile, for the first time, and more than doubled the community's per capita water supply. This project was funded by Environment Canada, and has inspired similar efforts in other arid regions around the world.

Fog harvesting is an innovative technology based upon the fact that fog can be captured and turned into liquid water under certain climatic conditions. Fog is defined as water vapor condensed into small water droplets just above the Earth's surface. Frequent fogs that occur along the coasts of Chile and Peru are called *camanchacas*, or coastal fog. Scientists have devised fog collection systems made of large pieces of canvas (nets 13 ft., or 4 m, high and 39 ft., or 12 m, long, made of ultraviolet-resistant polypropylene mesh) stretched horizontally between two upright poles. Nets are placed at right angles to prevailing coastal winds. As fog passes through the nets, the fog condenses into larger droplets of water—the process of cohesion described earlier. The liquid water slowly runs down the mesh and then drips into a trough or gutters beneath the canvas. Captured water flows into pipes and can be stored in tanks, cisterns, or reservoirs.[16]

The idea derived from the sight of great concentrations of vegetation in arid regions of Chile that seemed completely out of place. The source of their water supply was fog. The technology is so successful that the people of the remote fishing village of Chungungo, on the edge of the Atacama Desert, now have nearly 100 collectors that provide more than 10 gallons (40 l) of water per person per day, up from only 4 gallons (14 l) before the project started. Residents no longer must depend on water trucks for their freshwater supply. This project was one of the first large scale fog-harvesting projects in the world and has been very successful.[17] The following Guest Essay by Dr. Robert Schemenauer describes the process.

GUEST ESSAY

Fog Harvesting

by **Dr. Robert S. Schemenauer**
Executive Director, *FogQuest*

Dr. Schemenauer is Executive Director of *FogQuest: sustainable water solutions*, a registered charity that implements water projects in developing countries. Dr. Schemenauer is also an Adjunct Professor in the Department of Natural Resource Sciences at Thompson Rivers University in British Columbia. He received his

Ph.D. in physics from the University of Toronto, is member and past-chair of the Scientific Committee, 5th International Conference on Fog, Fog Collection and Dew, Muenster, Germany, and Emeritus Research Scientist, Environment Canada, Cloud Physics and Severe Weather Research Section.

Fog Deposition and Collection

Background Rain and snow are not the only sources of water in arid environments. Substantial amounts of water enter watersheds through the interception of fog droplets by vegetation. This process of fog deposition is especially productive in mountainous areas. The combination of fog, with low visibilities, and moderate winds, leads to high fog fluxes that can be utilized by vegetation or collected by artificial fog collectors. Fog water has been shown to be responsible for 20 to 30 percent of the water inputs in high elevation forests in the Eastern U.S. The percentage may approach 100 percent in isolated forests on the west coast of South America. A registered charity, FogQuest utilizes large fog collectors to provide clean water for villages in some of the world's driest environments. Presently there are operational fog collection projects in countries such as Chile, Peru, Guatemala, Cape Verde Islands, Eritrea, South Africa and Nepal.

There have been a number of reviews of the history of projects to collect fog water, e.g., Nagel (1956); Kerfoot (1968). As early as the 1890s reports on fog drip from trees in California were being written, and shortly after 1900 active projects to collect fog water took place in South Africa. In general, the water projects did not succeed due to a lack of understanding of the physics involved in the collection process. The modern era of fog collection research began in 1987 in Chile, with the cooperation of a team from Canada. Efficient, low-cost fog collectors were developed (Cereceda et al., 1992; Schemenauer et al., 1988) and are being used in locations where conventional sources of water are unavailable.

Properties of Fog As well as being present at low elevations as radiation fog, or advection fog off the ocean, fog is even more frequent on hills and mountains. In these locations, fog is produced by both the movement of clouds over the terrain and by the effects of the topography, which forces the air upwards where it can condense on microscopic particulates in the air to form fog on the hills. In meteorology, fog is present when the visibility is less than 1 km. Fog is composed of tiny water droplets. The droplet diameters range from 1 μm to 40 μm. These are the same sizes as cloud droplets, and indeed, fog is simply a cloud with its base on the ground. Because of their small sizes, fog droplets have very low fall velocities, typically less than 1 cm/s but up to 5 cm/s for the largest sizes. They thus move essentially horizontally with the wind (Schemenauer and Cereceda, 1994a). Fog liquid water contents typically range from 0.05 to 0.2 g/m^3 but can reach higher values when the bases of large convective clouds move over the terrain.

The collection of fog droplets depends on the diameter of the droplets, the wind speed and the nature of the collecting surface. In places where fog is frequent, windblown fog droplets are collected by vegetation in enormous quantities, large drops then form on the foliage, and these drops fall to the ground. This natural fog collection process sustains forests in the tropics (cloud forests) (Bruijnzeel et al., 2008), is an important water input to coastal forests in temperate latitudes, and is the sole source of water for trees and plants in some desert regions of the world (Follmann, 1963).

Amounts of Fog Water Available A simple way to measure horizontal fog fluxes is with a standard 1 m^2 fog water collection device known as a Standard Fog Collector (SFC). The construction and use is described in detail in Schemenauer and Cereceda (1994b). Evaluations of fog fluxes using an SFC have shown that on mountains in the deserts of Chile, Yemen and Eritrea, average fluxes ranged from 3 to 8 liters of water per square meter of vertical mesh surface per day.

Given the 50 percent efficiency of the SFCs, this means that in arid regions, in the driest times of the year, there was about 10 L m^{-2} per day of freshwater moving over the surface. In other countries, measurements of fog fluxes have shown average values as low as 1 L m^{-2} per day in Namibia and as high as 70 L m^{-2} per day in the Sultanate of Oman.

Fog collectors are made of an inexpensive, durable polypropylene or polyethylene mesh (Schemenauer and Joe, 1989). The mesh has fibers that efficiently collect the fog droplets and is woven to allow for rapid drainage of the collected water. The mesh is erected in vertical panels that are 4 m high by 10 or 12 m long (see Figure 2.13). Depending on the location, each panel produces 150 to 750 liters of potable water per day during the fog season. The operational projects to date have used from 2 to 100 fog collectors. Projects have shown success even in locations with as little as 1 mm per year annual precipitation.

The total quantity of water produced by large (40 to 48 m^2) fog collectors depends on the number of fog collectors installed and the collection rate at the site. The longest running site (Cereceda et al., 1992; Cereceda et al. 1997), in the coastal desert of Chile, supplied a village with clean water for ten years. At its maximum of 100 fog collectors, the fog çollector array at this site produced an average of 15,000 L of clean water each day of the year, in an arid region with an annual precipitation of only 60 mm. In order to have a successful project, a social need for water must be present, the correct meteorological conditions must exist, and the topography on several scales must be suitable (Schemenauer and Cereceda, 1994a). Normally in countries like Chile or Eritrea, fog collectors are grouped together to provide water for a school or a community, but FogQuest is now working in two villages in the western highlands of Guatemala where individual families have and maintain their own fog collectors. This has proven to be a good model for these villages. Two fog collectors produce about 400 L of potable water per day for a family (see Figure 2.14).

Fog Water Chemistry The chemistry of the fog droplets can be measured using several types of

FIG. 2.13 Fog collection system on a farm in Tojquia, Guatemala. The vertical mesh panels capture atmospheric moisture and allow it to trickle into the tank at the base of the collectors. The system provides drinking water and other uses for the community. *Source: FogQuest; Melissa Rosato.*

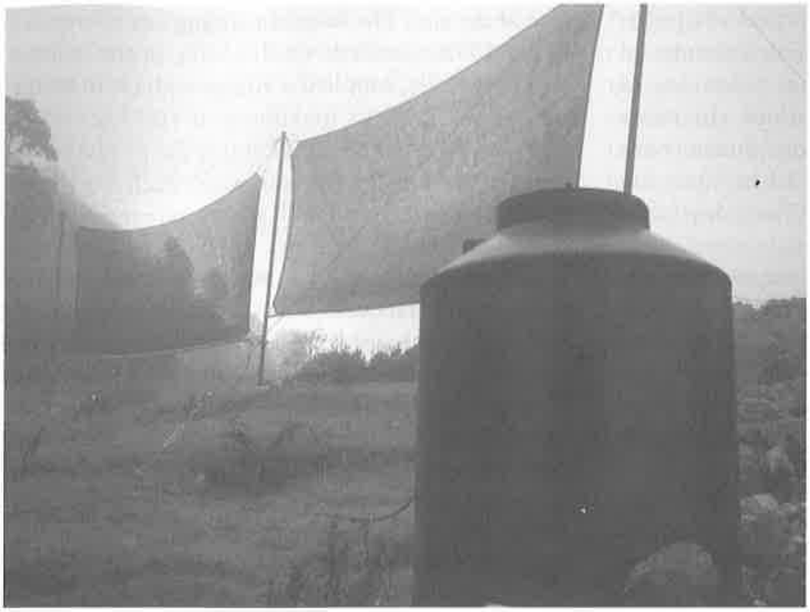

FIG. 2.14 Close up image of large plastic container to hold fog water in La Ventosa, Guatemala.

specialized collectors. Schemenauer and Cereceda (1992a) reported on the quality of both the fog water and the water from the fog collectors at the El Tofo site in Chile. They found that both sources of water met the WHO drinking-water standards for ions and for 23 heavy metals. Schemenauer and Cereceda (1992b) measured the concentrations of ions and 23 heavy metals in fog water at Ashinhaib in the Dhofar Mountains in the Sultanate of Oman. At this site on the coast of the Arabian Sea, all concentrations of ions and heavy metals fell within the WHO limits. Eckardt and Schemenauer (1998) found that ion concentrations measured in fog water collected in the Namib Desert near Gobabeb, Namibia were well within the WHO limits and in fact were even lower than previously reported values for Chile and the Sultanate of Oman. These three examples from the Chilean Coastal Desert, the Arabian Desert and the Namib Desert illustrate that fog water is a very suitable water supply for human consumption and thus for other uses as well.

Applications There are two major applications for fog water collection in arid regions:

1. Fog collectors can provide water meeting World Health Organization drinking-water standards to rural communities and groups of homes; this water is inexpensive to produce and can be delivered to the homes by gravity flow.
2. Fog collectors can provide water for reforestation of ridge lines and the upper parts of mountains where it is impractical to import water from conventional sources; the fog water can be delivered to drip irrigation systems by gravity flow, and the resulting forests, if properly situated, can become self-sustaining by directly collecting fog water. A major experiment funded by the European Union took place in the late 1990s to investigate techniques to reforest the hills in the Peruvian coastal desert. Another project started in northern Chile in 2008 to build a plantation at the Atacama Desert Center using fog collectors as the source of water.

Discussion Fog is present in almost every country on Earth. It is composed of droplets of water, and these droplets when combined by the billions upon billions become a major water source for vegetation and can be a managed water supply for small communities. Reforesting clear-cut areas on mountains, especially if they are in zones with frequent fog, can result in a sustainable forest, lead to increased runoff, and provide more water in aquifers. Forests created on foggy desert hilltops can sequester carbon from the atmosphere and help address the buildup of greenhouse gases. These are the large-scale applications for fog collection. They are also longer-term applications. On shorter time scales, villages that lack either adequate amounts of water, or potable water due to contamination of the aquifers, can be given clean water with simple, passive, fog collectors (see Figure 2.15).

In summary, the hydrologic cycle represents the continuous movement of water from the atmosphere to the land surface, from the land, rivers, lakes, and groundwater to the oceans, and from the oceans back to the atmosphere. The movement of water through the hydrologic cycle distributes moisture around the world through precipitation, runoff, storage, evaporation and transpiration, and condensation. Predictable hydrologic patterns and changes to those patterns, caused by natural events or human activities, combine to create our climate and weather around the world.

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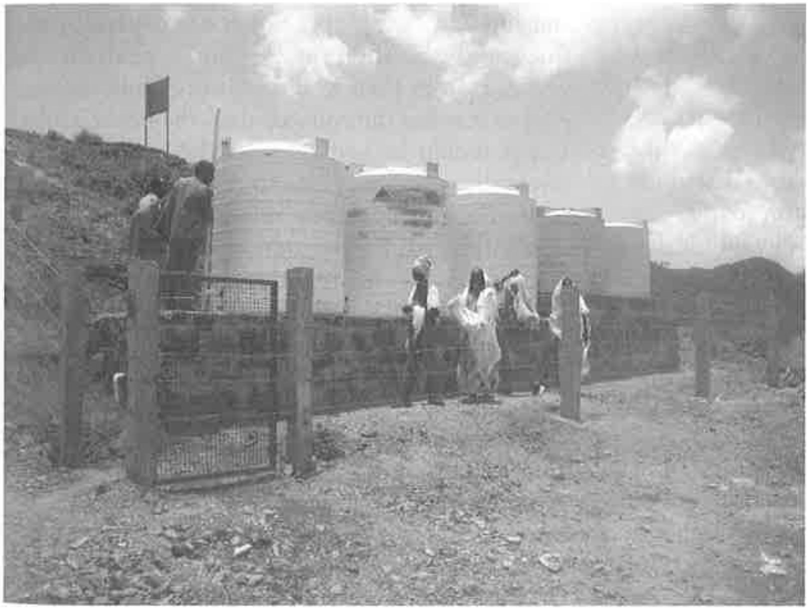

FIG. 2.15 Each of the five tanks holds 5000 liters (1300 gal) of fog water for use by a school and the community of Arberobue, Eritrea, in northeast Africa.