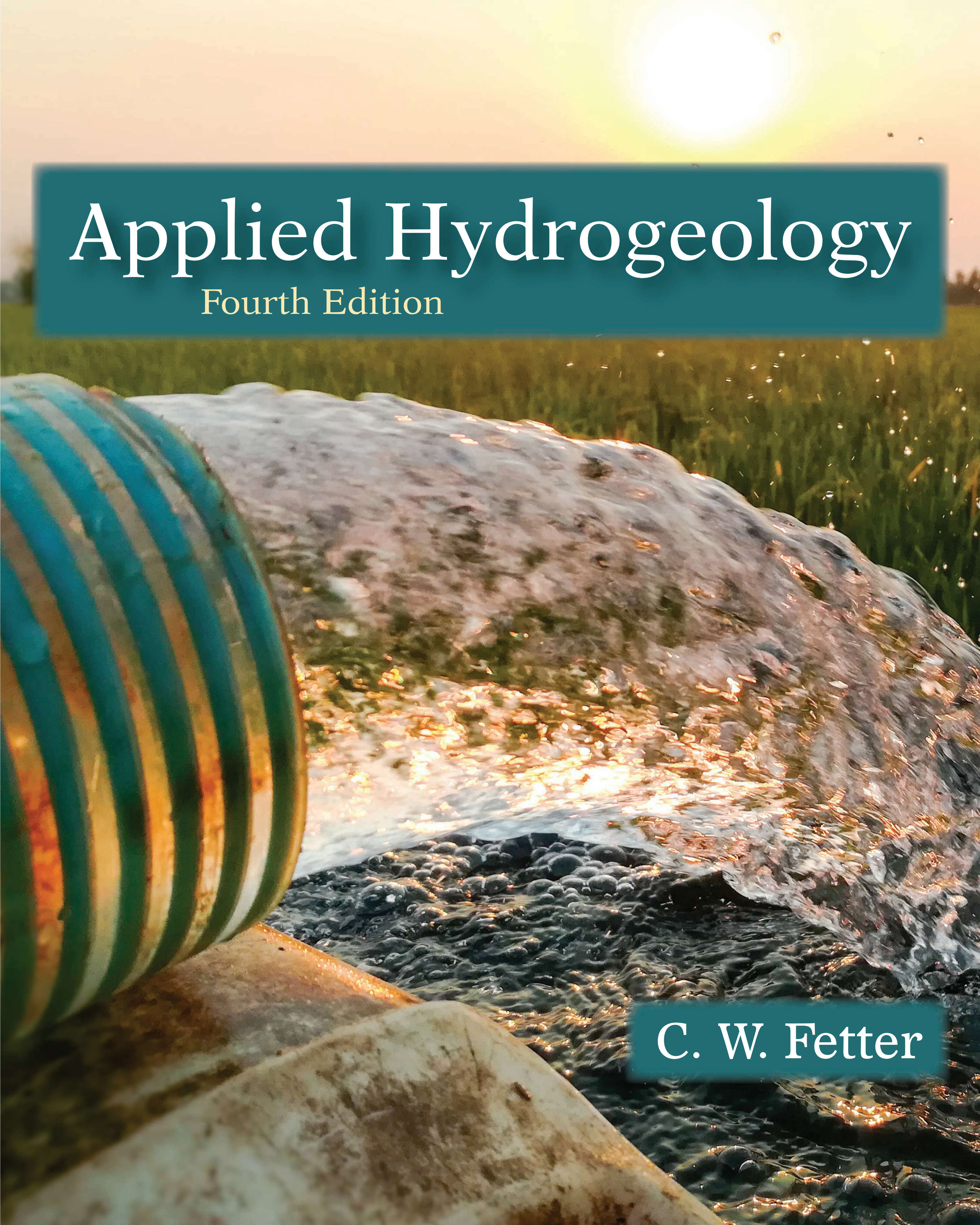

Applied Hydrogeology

Fourth Edition

C. W. Fetter

Conversion values for hydraulic conductivity

1 gal/day/ft^2 = 0.0408 m/day
1 gal/day/ft^2 = 0.134 ft/day
1 gal/day/ft^2 = 4.72×10^{-5} cm/sec
1 ft/day = 0.305 m/day
1 ft/day = 7.48 gal/day/ft^2
1 ft/day = 3.53×10^{-4} cm/sec
1 cm/sec = 864 m/day
1 cm/sec = 2835 ft/day
1 cm/sec = 21,200 gal/day/ft^2
1 m/day = 24.5 gal/day/ft^2
1 m/day = 3.28 ft/day
1 m/day = 0.00116 cm/sec

Applied Hydrogeology

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C. W. Fetter

late of
University of Wisconsin–Oshkosh

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This book is dedicated to my wife, Nancy Blessing Fetter,
and to my children and their families:

Bill, Barb, Katie and Sarah Fetter

Rob and Abby Fetter

Elizabeth Fetter

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PREFACE

Hydrogeology is now considered to be a core course in the curriculum of undergraduate geology programs as well as many fields of engineering. There is ongoing demand for persons with training in hydrogeology by consulting organizations, state and federal regulatory agencies, and industrial firms. Most of the employment in hydrogeology is in the environmental area. This is a book that will help prepare students for either a career in hydrogeology or in other areas of environmental science and engineering where a strong background in hydrogeology is needed.

Applied Hydrogeology is intended as a textbook for an introductory course in hydrogeology taught either at the advanced undergraduate level, or as a dual-level undergraduate/graduate course. It is also useful in helping individuals who are preparing to take state ex aminations for professional registration as a hydrologist or hydrogeologist. It can be found as a reference book in the personal library of many working professionals.

The reader is expected to have a working knowledge of college algebra, and calculus is helpful, but not necessary, for practical understanding of the material. A background in college chemistry is necessary to understand the chapter on water chemistry. The book stresses the application of mathematics to problem-solving rather than the derivation of theory. To this end you will find many example problems with step-by-step solutions. Case studies in many chapters enhance understanding of the occurrence and movement of ground water in a variety of geological settings. A glossary of hydrogeological terms makes this book a valuable reference.

The fourth edition contains new case studies and end-of-chapter problems. In most cases the problems are paired. An odd-numbered problem will have the answer given in a section in the back of the book, followed by an even-numbered problem without the answer. Many chapters in the fourth edition also contain a section called Analysis, with non-numerical questions. The use of spreadsheet programs, such as Microsoft® Excel, in hydrogeology is introduced here.

Included with the text are working student versions of three computer programs that are used by ground-water professionals. They have been furnished free of charge by the software publishers. No technical support is furnished for these programs, either by the author or the software publisher. However, they are easy to use and come with tutorials and documentation.

The following reviewers of the Third Edition provided helpful suggestions for the Fourth Edition: Gary S. Johnson, University of Idaho; Larry Murdoch, Clemson University; Claude Epstein, Richard Stockton College of New Jersey; David L. Brown, California State University at Chico; F. Edwin Harvey, University of Nebraska at Lincoln; Edward L. Shuster, Rensselaer Polytechnic Institute; Willis D. Weight, Montana Tech. of the University of Montana; Larry D. McKay, University of Tennessee at Knoxville; Laura L. Sanders, Northwestern Illinois University; Jean Hoff, St. Cloud State University; and Jim Butler, Kansas Geological Survey. Dr. Carl Mendoza of the University of Alberta peer reviewed the Fourth Edition and made many helpful suggestions and corrections.

I am grateful to Larry Murdoch and Rex Hodges of Clemson University for introducing me to the use of spreadsheet ground-water flow models. I would especially like to thank Glenn Duffield of Hydrosolve, Inc. for furnishing the student version of AQTESOLV, Pat Delaney of Waterloo Hydrogeologic Inc. for furnishing the student version of Visual MODFLOW, and Kirk Hemker for the use of FLOWNETLT. Todd Rayne of Hamilton College has prepared the solution manual for the problems. Patrick Lynch has been very supportive through the course of my preparation of this revision.

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ABOUT THE AUTHOR

C. W. Fetter received a B.A. degree in chemistry from DePauw University, an M.A. in geology and a Ph.D. in hydrogeology from Indiana University. He has practiced as a professional hydrogeologist since 1966, and is registered as both a professional geologist and professional engineer.

He was on the faculty of the University of Wisconsin–Oshkosh for 25 years, where he was department chair for 15 years. Since his retirement from UW–Oshkosh in 1996 he has been a full time consultant in environmental hydrogeology. His clients have included the United States Environmental Protection Agency, the Wisconsin Department of Justice, the United States Department of Justice, Fortune 500 corporations, insurance companies, municipal government, and attorneys at law. Dr. Fetter has been an expert witness in legal proceedings on numerous occasions.

In 1996 he received the Excellence in Science and Engineering Award from the Association of Ground Water Scientists and Engineers in recognition of his two books about hydrogeology. In 1998 he received the Hydrogeologist of the Year award from the Wisconsin Ground Water Association.

Applied Hydrogeology

1 CHAPTER

Water

In the winter of wet years the streams ran full-freshet, and they swelled the river until it sometimes raged and boiled bank full, and then it was a destroyer. The river tore the edges of the farm lands and washed whole acres down; it toppled barns and houses into itself, to go floating and bobbing away. It trapped cows and pigs and sheep and drowned them in its muddy brown water and carried them to the sea. Then when the late spring came the river drew in from its edges and the sand banks appeared. And in the summer the river didn't at all run above ground.

There were dry years too . . . The water came in a thirty-year cycle. There would be five or six wet and wonderful years when there might be nineteen to twenty-five inches of rain, and the land would shout with grass. Then would come six or seven pretty good years of twelve to sixteen inches of rain. And then the dry years would come, and sometimes there would be only seven or eight inches of rain. The land dried up . . . And it never failed that during the dry years the people forgot the rich years, and during the wet years they lost all memory of the dry years. It was always that way.

East of Eden, John Steinbeck, 1952

1.1 Water

John Steinbeck wrote the above words 50 years ago to describe the hydrology of the Salinas Valley in northern California. In doing so he revealed an attitude toward water that was held by many in the early part of the twentieth century. Water was always assumed to be available and no one worried about its longevity until it seemed threatened. We perhaps have a more realistic attitude today and know that we must preserve and protect our precious and limited natural resources, including water.

Although our intentions toward preserving the environment may be good, we sometimes act without full consideration of all possible outcomes. In 1990, Congress passed the Clean Air Act. To reduce the mass of smog-creating chemicals released by vehicles, gasoline sold in certain urban areas was required to be reformulated, starting in 1992, so that it contained at least 2% oxygen. At the time there were only two chemicals considered practical to add to gasoline, ethanol and methyl tertiary butyl ether (MTBE). At that time, no one knew if MTBE posed any potential health risks if ingested, but its high solubility in water was known. In addition, it was well known that many gasoline retailers had leaking underground storage tanks.

By 1996, about 100 million barrels of MTBE were used to formulate gasoline in the United States (Andrews 1998). Reformulated gasoline contains 10% MTBE. While air quality has improved in urban areas where MTBE is used in reformulated gasoline, not surprisingly we now find that ground water in some areas has been contaminated with it. Most chemicals found in gasoline degrade rather quickly in the earth, but not MTBE; it is persistent as it resists biodegradation.

As of 2000 there are still no federal drinking-water standards for MTBE; the toxicity is still being evaluated. Yet, legislation was passed a decade ago that could reasonably have been expected to result in the release of MTBE into ground water. In the spring of 2000 the Environmental Protection Agency (EPA) decided to phase out the use of MTBE in gasoline due to ground-water contamination. The lesson to be learned here is even the best of intentions can have unanticipated and extremely undesirable consequences on our limited water resources.

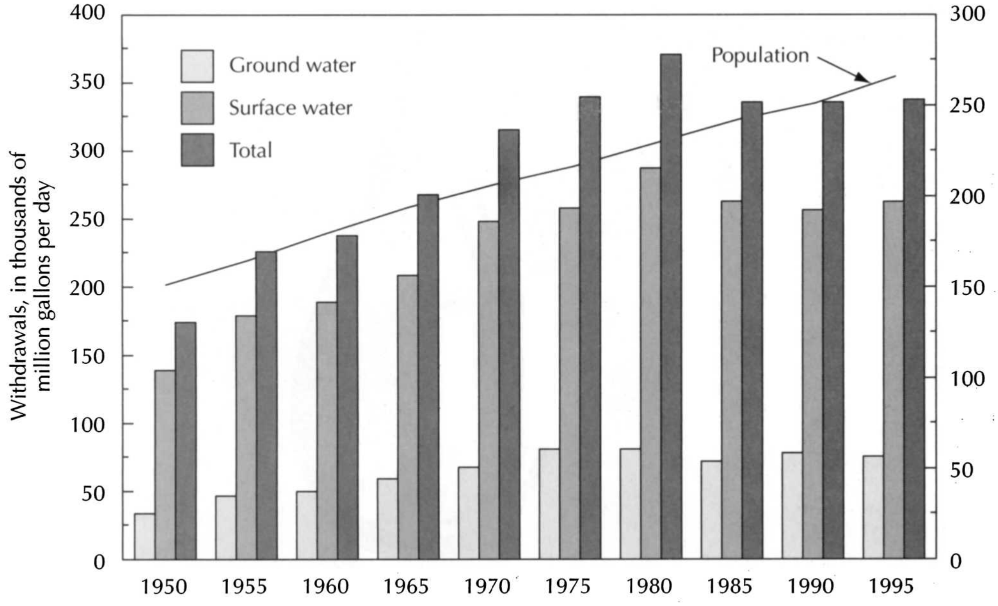
Water is the elixir of life; without it life is not possible. Although many environmental factors determine the density and distribution of vegetation, one of the most important is the amount of precipitation. Agriculture can flourish in some deserts, but only with water either pumped from the ground or imported from other areas.

Civilizations have flourished with the development of reliable water supplies—and then collapsed as their water supplies failed. This book is about the occurrence of water, both at the surface and in the ground. A person requires about 3 quarts (qt) or liters (L) of potable water per day to maintain the essential fluids of the body. Primitive people in arid lands existed with little more than this amount as their total daily consumption. A single cycle of an older flush toilet may use 5 gallons (gal) (19 L) of water. In New York City the per capita water usage exceeds 260 gal (1000 L) daily; much of this is used for industrial, municipal, and commercial purposes. For personal purposes, the typical American uses 50 to 80 gal (200 to 300 L) per day. Even greater quantities of water are required for energy and food production.

In 1995, the total off-stream water use in the United States was estimated to be 402 billion gallons (1520 billion liters) per day of fresh and saline water. This does not include water used for hydroelectric power generation and other in-stream uses, but does include water used for thermoelectric power plant cooling. Fresh-water use in 1995 included 77.5 billion gallons (290 billion liters) per day of ground water and 263 billion gallons (995 billion liters) per day of surface water (Figure 1.1). Per capita fresh-water use was 1280 gal (4850 L) per day. Consumptive use of water, that is, water evaporated during use, was about 81 billion gallons (300 billion liters) per day (Solley, Pierce, & Perlman 1998).

Total water use in the United States peaked in 1980 and has declined since then. The estimated total water use in 1995 was 2% less than in 1990 and 10% less than in 1980. Water use for public water supply has shown a continual increase since 1950 due to increasing population. Public water supply (40.2 billion gallons in 1995) accounts for 10% of the total water use in the United States. The largest uses of water are for cooling of electric power generation facilities and for irrigation.

Although it had generally been assumed that economic growth results in increased water use, from 1975 to 1995 per capita water use in the United States actually declined by



▲ FIGURE 1.1
Trends in fresh ground- and surface-water withdrawals and population in the United States.
Source: Solley, Pierce, and Perlman, 1998.

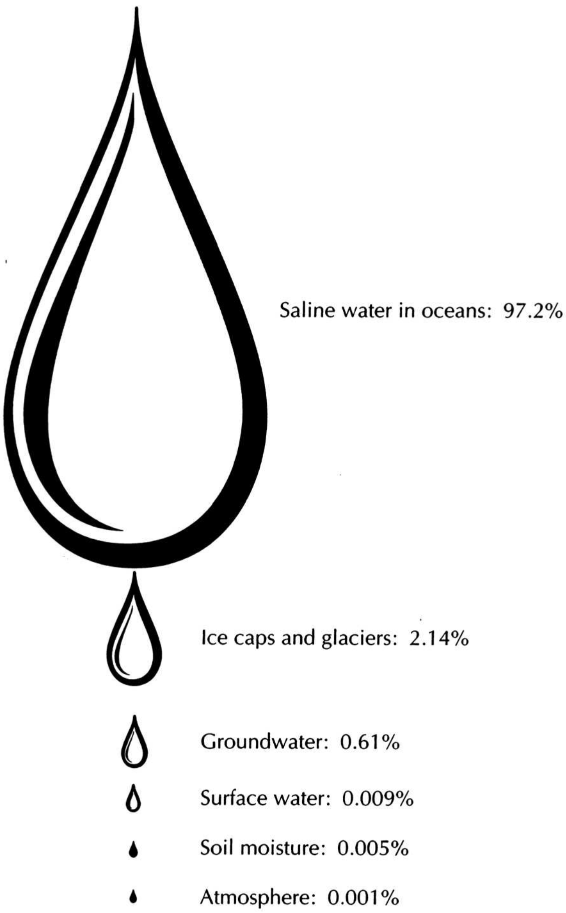
25%. This can be attributed to increased conservation of water (Wood 1999). As an example, toilets now sold in the United States can use no more than 1.5 gal. (6 L) per flush.

1.2 Hydrology and Hydrogeology

As viewed from a spacecraft, the earth appears to have a blue-green cast owing to the vast quantities of water covering the globe. The oceans may be obscured by billowing swirls of clouds. These vast quantities of water distinguish Earth from the other planets in the solar system. **Hydrology** is the study of water. In the broadest sense, hydrology addresses the occurrence, distribution, movement, and chemistry of all waters of the earth. **Hydrogeology** encompasses the interrelationships of geologic materials and processes with water. (A similar term, **geohydrology,** is sometimes used as a synonym for hydrogeology, although it more properly describes an engineering field dealing with subsurface fluid hydrology.) The physiography, surficial geology, and topography of a drainage basin, and the vegetation, influence the relationship between precipitation over the basin and water draining from it. The creation and distribution of precipitation is heavily influenced by the presence of mountain ranges and other topographic features. Running water and ground water are geologic agents that help shape the land. The movement and chemistry of ground water is heavily dependent upon geology.

Hydrogeology is both a descriptive and an analytic science. Both the development and management of water resources are important parts of hydrogeology as well. An account of the water supply of the world would reveal that saline water in the oceans accounts for 97.2% of the total. Land areas hold 2.8% of the total. Ice caps and glaciers hold 2.14%; ground water to a depth of 13,000 feet (ft) [4000 meters (m)] accounts for 0.61% of the total; soil moisture, 0.005%; fresh-water lakes, 0.009; rivers, 0.0001%; and saline lakes, 0.008% (Feth 1973). More than 75% of the water in land areas is locked in glacial ice or is saline (Figure 1.2).

▶ FIGURE 1.2
Distribution of the world water supply



1.3 The Hydrologic Cycle

Only a small percentage of the world's total water supply is available to humans as fresh water. More than 98% of the available fresh water is ground water, which far exceeds the volume of surface water. At any given time, only 0.001% of the total water supply is in the atmosphere. However, atmospheric water circulates very rapidly, so that each year enough water falls to cover the conterminous United States to a depth of 30 inches (in.) [75 centimeters (cm)]. Of this amount, 22 in. (55 cm) are returned to the atmosphere through evaporation and transpiration by growing plants, whereas 8 in. (20 cm) flow into the oceans as rivers (Federal Council for Science and Technology 1962). Although the previous sentence implies that the **hydrologic cycle** begins with water from the oceans, the cycle actually has no beginning and no end. As most of the water is in the oceans, it is convenient to describe the hydrologic cycle as starting with the oceans. Water evaporates from the surface of the oceans. The amount of evaporated water varies, being greatest near the equator, where solar radiation is more intense. Evaporated water is pure, because when it is carried into the atmosphere the salts of the sea are left behind. Water vapor moves through the atmosphere as an integral part of the phenomenon we term "the weather." When atmospheric conditions are suitable, water vapor condenses and forms droplets. These droplets may fall to the sea or onto land or may revaporize while still aloft.

Precipitation that falls on the land surface enters various pathways of the hydrologic cycle. Some water may be temporarily stored on the land surface as ice and snow or water in puddles, which is known as **depression storage.** Some of the rain or melting snow will drain across the land to a stream channel. This is termed **overland flow.** If the surface soil is porous, some rain or melting snow will seep into the ground by a process called **infiltration.**

Below the land surface the soil pores contain both air and water. The region is known as the **vadose zone,** or **zone of aeration.** Water stored in the vadose zone is called **vadose water.** At the top of the vadose zone is the belt of soil water. This is the zone where the roots of plants can reach. The soil water contained in the belt of soil water can be drawn into the rootlets of growing plants. As the plant uses the water, it is **transpired** as vapor to the atmosphere. Under some conditions water can flow laterally in the vadose zone, a process known as **interflow.** Water vapor in the vadose zone can also migrate back to the land surface to **evaporate.** Excess vadose water is pulled downward by gravity, a process known as **gravity drainage.** It passes through the intermediate belt to the **capillary fringe.** In the capillary fringe, the pores are filled with capillary water so that the saturation approaches 100%; however, the water is held in place by capillary forces.

At some depth, the pores of the soil or rock are saturated with water. The top of the **zone of saturation** is called the **water table.** Water stored in the zone of saturation is known as **ground water.** It then moves as **ground-water flow** through the rock and soil layers of the earth until it discharges as a spring or as seepage into a pond, lake, stream, river, or ocean (Figure 1.3).

Water flowing in a stream can come from overland flow or from ground water that has seeped into the streambed. The ground-water contribution to a stream is termed **baseflow,** while the total flow in a stream is **runoff.** Water stored in ponds, lakes, rivers, and streams is called **surface water.**

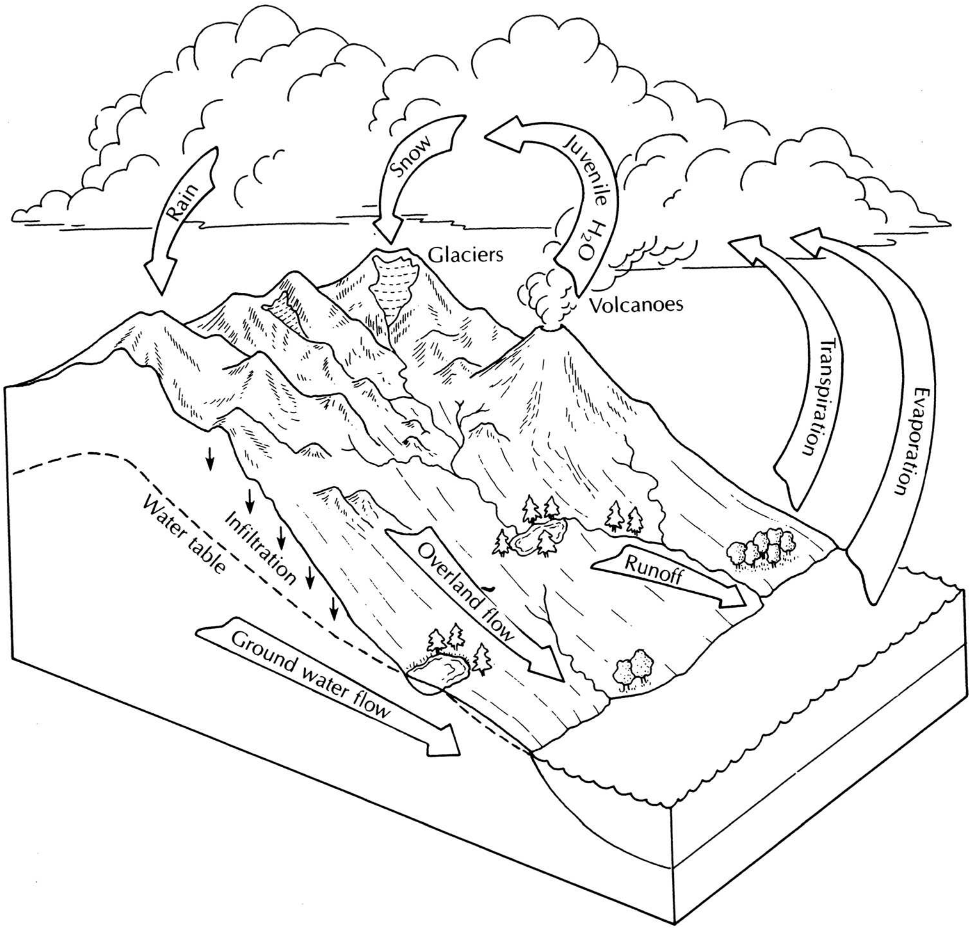
Evaporation is not restricted to open water bodies, such as the ocean, lakes, streams, and reservoirs. Precipitation intercepted by leaves and other vegetative surfaces can also evaporate, as can water detained in land-surface depressions or soil moisture in the upper layers of the soil. Direct evaporation of ground water can take place when the saturated zone is at or near the land surface. Transpiration by plants and evaporation from land surfaces are lumped together as **evapotranspiration.**

Magmatic water is contained within magmas deep in the crust. If the magma reaches the surface of the earth or the ocean floor, the magmatic water is added to the water in the hydrologic cycle. Steam seen in some volcanic eruptions is ground water that comes into contact with the rising magma and is not magmatic water. Some of the water in the ocean sediments is subducted with the sediments and is withdrawn from the hydrologic cycle. This water may eventually become part of a magma.

Figure 1.4 is a schematic drawing of the hydrologic cycle showing the major reservoirs where water is stored and the pathways by which water can move from one reservoir to others. Figure 1.5 illustrates the classification system for underground water.

1.4 Energy Transformations

The hydrologic cycle is an open system in which solar radiation serves as a source of constant energy. This is most evident in the evaporation and atmospheric circulation of water. The energy of a flowing river is due to the work done by solar energy, evaporating water from the ocean surface and lifting it to higher elevations, where it falls to earth. When water changes from one state to another (liquid, vapor, or solid), an accompanying change occurs in the heat energy of the water. The heat energy is the amount of thermal energy contained by a substance. A *calorie* (cal) of heat is defined as the energy necessary to raise the temperature of 1 gram (g) of pure water from 14.5°C to 15.5°C. At other temperatures it takes approximately 1 cal to change the temperature of 1 g of water 1°C. The evaporation of water requires an



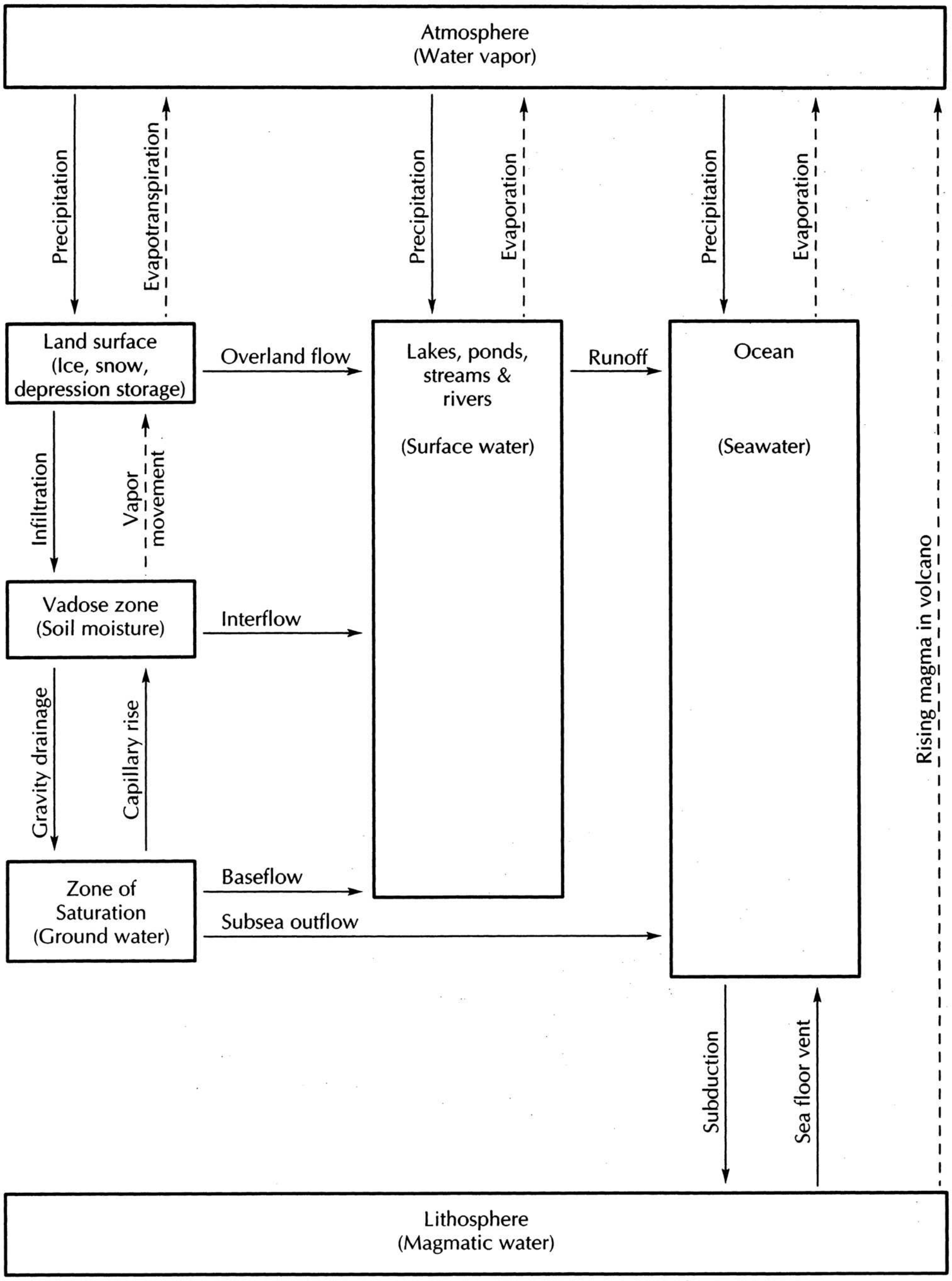
▲ FIGURE 1.3
The hydrologic cycle.

input of energy, called the *latent heat of vaporization.* At environmental temperatures (0°C to 40°C), the latent heat of vaporization H_v, in calories per gram of water, can be found by

$$H_v = 597.3 - 0.564T \tag{1.1}$$

where T is the temperature in degrees Celsius.

When water vapor condenses to a liquid form, an equivalent heat amount called the *latent heat of condensation* is released. This factor can also be obtained from Equation 1.1. To melt 1 g of ice at 0°C, 79.7 cal of heat must be added, to create the *latent heat of fusion.* The resulting water also has a temperature of 0°C, although the gram of water holds more heat energy than the gram of ice. Water can also pass directly from a solid state to a vapor state by a process called *sublimation.* The energy necessary to accomplish this is the sum of the latent heat of vaporization and the latent heat of fusion. At 0°C, this is 677 cal/g. Freezing of water releases 79.7 cal/g, and the formation of frost at 0°C releases 677 cal/g. The transportation of water through the hydrologic cycle and the accompanying heat transfers are vital to the heat balance of the earth. At the equator, the amount of solar radiation is fairly constant through the year, whereas at the poles it varies from near zero during the polar winter to significant amounts during the polar summer. During polar winters, the land is in shadow so the sun does not strike the ground; during the summers, the sun shines con-



▲ FIGURE 1.4
Schematic drawing of the hydrologic cycle. Movement of liquid water is shown by a solid line and movement of water vapor is shown by a dashed line.

tinuously. Over the year, the Northern Hemisphere northward of 38° latitude has a net heat loss, as the outgoing terrestrial radiation to space exceeds the incoming solar radiation that is absorbed. Between the equator and 38° N, there is more solar radiation absorbed than terrestrial radiation lost to space. To balance these anomalies, heat is transferred by currents in the oceans and through the atmosphere as movement of air masses and water vapor, thus creating climatic conditions and changing weather patterns that profoundly affect the hydrologic cycle.

Vadose zone (zone of aeration)	Vadose water	Soil water	Belt of soil water
		Intermediate vadose water	Intermediate belt
Water table		Capillary water	Capillary fringe
Zone of saturation (phreatic zone)	Ground water		

▲ FIGURE 1.5
Classification of water beneath the land surface.

1.5 The Hydrologic Equation

The hydrologic cycle is a useful concept but is quantitatively rather vague. The **hydrologic equation** provides a quantitative means of evaluating the hydrologic cycle. This fundamental equation is a simple statement of the *law of mass conservation.* It may be expressed as

$$\text{Inflow} = \text{outflow} \pm \text{changes in storage}$$

If we consider any hydrologic system—for instance, a lake—it has a certain volume of water at a given time. Several inflows add to this water volume: precipitation that falls on the lake surface, streams that flow into the lake, ground water that seeps into the lake, and overland flow from nearby land surfaces. Water also leaves the lake through evaporation, transpiration by emergent aquatic vegetation, outlet streams, and ground-water seepage from the lake bottom. If, over a given time period, the total inflows are greater than the total outflows, the lake level will rise as more water accumulates. If the outflows exceed the inflows over a time period, the volume of water in the lake will decrease. Any differences between rates of inflow and outflow in a hydrologic system will result in a change in the volume of water stored in the system. The hydrologic equation can be applied to systems of any size. It is as useful for a small reservoir as it is for an entire continent. The equation is time dependent. The elements of inflow must be measured over the same time periods as the outflows.

The basic unit of surface-water hydrology is the **drainage basin,** or **catchment,** which consists of all the land area sloping toward a particular discharge point. It is outlined by surface-water boundaries, or **topographic divides.** In ground-water hydrology, we utilize the concept of a **ground-water basin,** which is the subsurface volume through which ground water flows toward a specific discharge zone. **Ground-water divides** surround it. The boundaries of a surface-water basin and the underlying ground-water basin do not necessarily coincide, although the water budget of the area must account for both ground and surface water. Many times hydrologic budgets are made for areas surrounded by political boundaries and not hydrologic boundaries; however, one still must know the location of the hydrologic boundaries, both surface and subsurface, to perform a water-budget analysis. Water will flow from the hydrologic boundary toward the point of discharge and hence may flow into the study area if the boundary of the study area does not coincide with the hydrologic boundary. The hydrologic inputs to an area may include (1) precipitation; (2) surface-water inflow into the area, including runoff and overland flow; (3) ground-water inflow from outside the area; and (4) artificial import of water into the area through pipes and canals. The hydrologic outputs from an area may include (1) evapotranspiration from land areas; (2) evaporation of surface water; (3) surface water runoff; (4) ground-water outflow; and (5) artificial export of water through pipes and canals. The changes in storage necessary to balance the hydrologic equation include changes in the volume of (1) surface water in streams, rivers, lakes, and ponds; (2) soil moisture in the vadose zone; (3) ice and snow at the surface; (4) temporary depression storage; (5) intercepted water on plant surfaces; and (6) ground water below the water table. The application of the hydrologic equation to a watershed is illustrated in the following case study.

Case Study: Mono Lake

> *Half a dozen little mountain brooks flow into Mono Lake, but not a stream of any kind flows out of it. What it does with its surplus water is a dark and bloody mystery.*
>
> Mark Twain

Mono Lake lies on the eastern slope of the Sierra Nevada near the east entrance to Yosemite National Park. Mono Lake is a terminal lake, which means that although water enters the lake by precipitation and by streams and ground water flowing into it, water can leave only by evaporation. The lake level fluctuates with climatic changes. The volume of water that leaves the lake by evaporation is the product of the surface area times the depth of evaporation. If the volume that leaves by evaporation is exactly balanced by the inflow, the lake level will not change. If the inflow exceeds evaporation, the water level will rise. If the inflow is less than evaporation, the lake level will fall. The Mono Lake basin has an area of 695 square miles (mi^2) [180,000 hectares (ha)]. Inputs to the lake under natural conditions are direct precipitation, with an estimated annual average of 8 in. (0.2 m); runoff from the land areas via gauged streams, which is estimated to average 150,000 acre-feet (ac-ft)* per year [1.85×10^8 cubic meters (m^3)]; and ungauged runoff and ground-water inflow, which is estimated to average 37,000 ac-ft per year (4.56×10^7 m^3). The average annual rate of lake evaporation is about 45 in. (1.1 m) (Vorster 1985). When it was first surveyed in 1856, the elevation of Mono Lake was 6407 ft (1953 m) above sea level. Climatic effects of moister and drier periods caused the lake level to rise to as much as 6428 ft (1959 m) in 1919 and then to fall to 6410 ft (1954 m) by 1941. In that year, water was first diverted from four of the five major streams feeding Mono Lake into the Los Angeles Aqueduct and then into southern California.

---

*An acre-foot is a measure of the volume of water that is commonly used in the western United States. It is the amount of water that will cover an acre of land to a depth of 1 ft (43,560 ft^3).