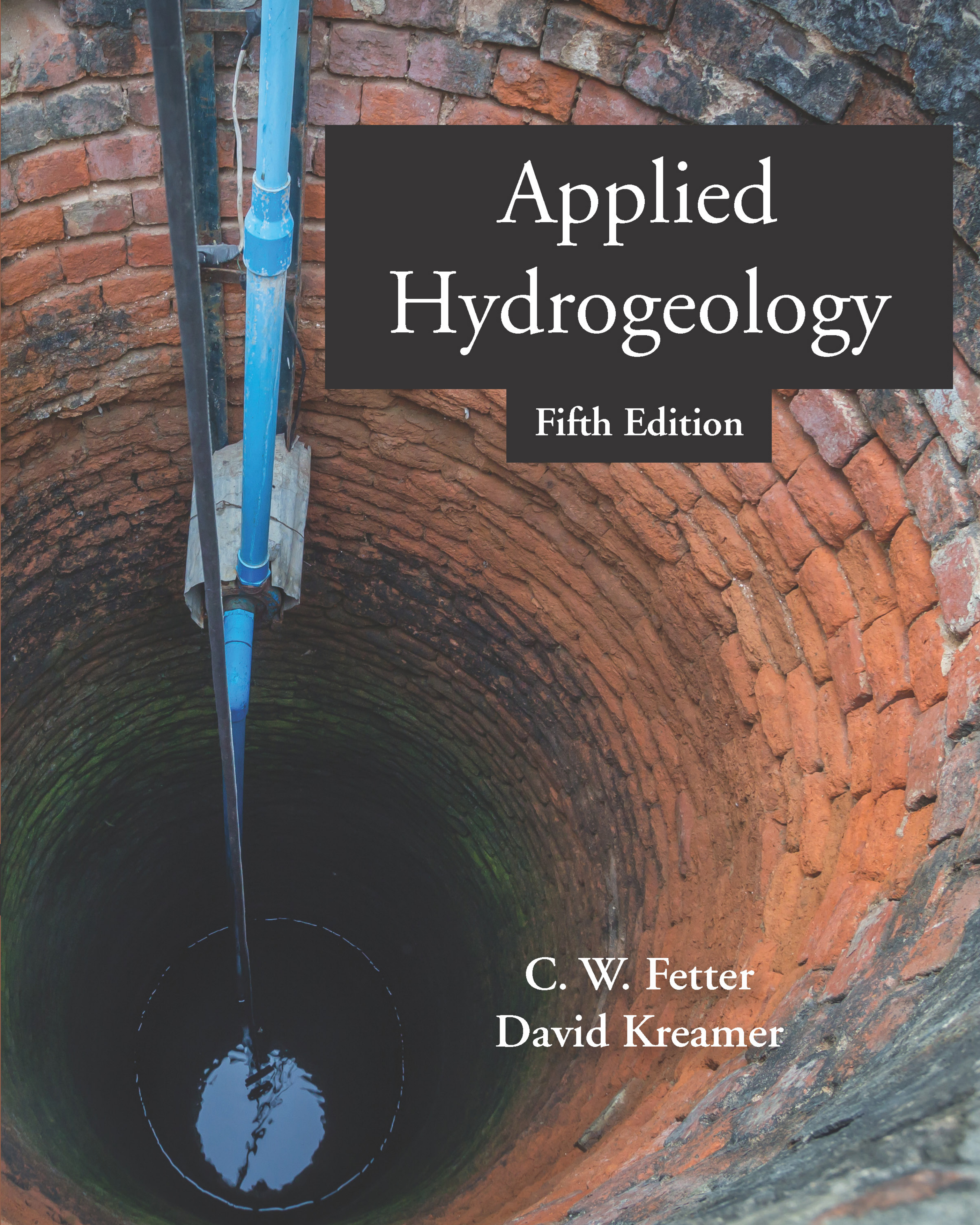

Applied Hydrogeology

Fifth Edition

C. W. Fetter
David Kreamer

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This book is dedicated to

Nancy Blessing Fetter,
and to her children and their families:
Bill, Barb, Katie, and Sarah Fetter
Rob and Abby Fetter
Elizabeth Fetter

and to

Bill and Marie Kreamer,
and their children, grandchildren, and great-grandchildren

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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 examinations 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 fifth 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 fifth 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 is a working demo of the computer program AQTESOLV that is used by groundwater professionals. It has been furnished free of charge by the software publisher. No technical support is furnished for this program, either by the author or the software publisher. However, it is easy to use and comes with examples and some documentation.

The following reviewers of the previous editions have provided helpful suggestions: 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, Northeastern 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 previous editions and has made many helpful suggestions and corrections.

We are grateful to Larry Murdoch and Rex Hodges of Clemson University for introducing the use of spreadsheet groundwater flow models. We would especially like to thank Glenn Duffield of HydroSOLVE, Inc. for furnishing the student version of AQTESOLV. Patrick Lynch has been very supportive through the course of preparation of this and previous revisions. Thanks also to Duane Hampton of Western Michigan University and Wayne Belcher of the United States Geological Survey for their insightful comments. The fine editorial work of Dakota West and the support of Don Rosso of Waveland Press, Inc., is also gratefully acknowledged.

The core of this text was written by the late C. W. "Bill" Fetter, Jr., who was an Emeritus Professor of Hydrogeology at the University of Wisconsin Oshkosh. The text has been updated and an international perspective has been added to what has previously been geared more exclusively toward users in the United States. The work of Bill Fetter will serve as an enduring legacy to his contributions to the field of hydrogeology.

David K. Kreamer
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University of Nevada, Las Vegas
President, International Association of Hydrogeologists

ABOUT THE AUTHORS

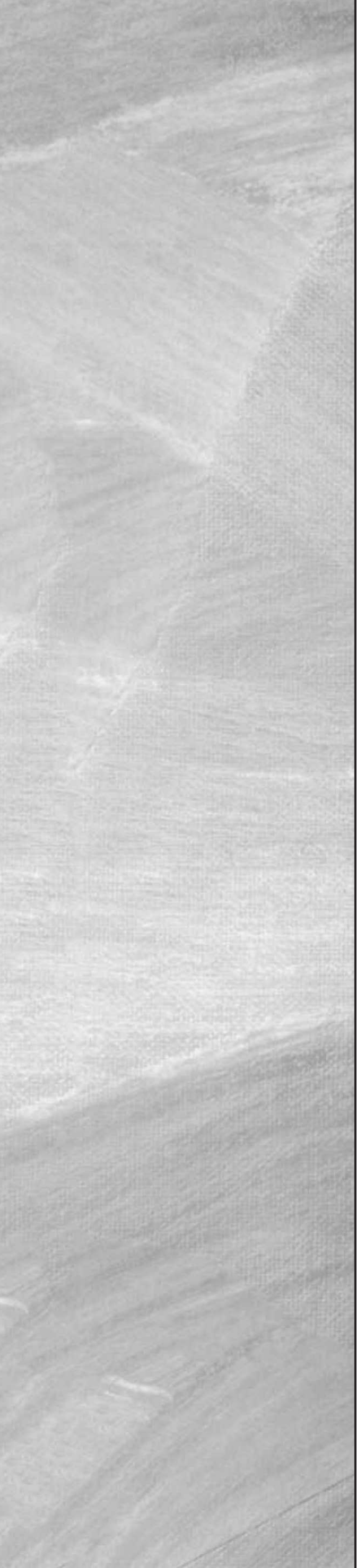
C. W. Fetter received a BA degree in chemistry from DePauw University, an MA in geology and a PhD in hydrogeology from Indiana University. He practiced as a professional hydrogeologist beginning in 1966 and was registered as both a professional geologist and professional engineer.

He was on the faculty of the University of Wisconsin–Oshkosh for 25 years, where he was department chair for 15 years. After his retirement from UW–Oshkosh in 1996 he was a full-time consultant in environmental hydrogeology. His clients 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 served as 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.

David K. Kreamer is a Professor of Geoscience, and also Graduate Faculty in the Department of Civil and Environmental Engineering and Construction, and is past Director of the interdisciplinary Water Resources Management Graduate Program at the University of Nevada, Las Vegas. He also serves as faculty in the Hydrologic Sciences Program at the University of Nevada, Reno. His PhD is in Hydrology from the University of Arizona, and he was an Assistant Professor in Civil Engineering at Arizona State University. He was elected President of the International Association of Hydrogeologists from 2020 to 2024.

David's research includes environmental contamination, spring sustainability, and clean water supply in developing nations, with over 75 professional publications. He has given over 150 invited lectures, seminars, and workshops in recent years for the US Environmental Protection Agency, US Bureau of Land Management, the National Ground Water Association, and the Superfund University Training Institute; presented short courses for over half the states or commonwealths in the United States; and lectured for other groups. He has given presentations at over forty universities, and has spoken in Europe, Asia, the Caribbean, Pacific Island nations, South America, Africa, and the Middle East. He has served on the Board of Directors of the National Ground Water Association's Division of Scientists and Engineers, and served on the Board of Directors and as President of the Universities Council on Water Resources.



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 almost three quarters of a century 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.

The importance of water has been echoed throughout history from all areas of the globe. In a later time, on the opposite hemisphere, Mikhail Gorbachev, general secretary of the Communist Party (1985–1991) and the last leader of the Soviet Union (president 1990–1991), wrote:

> Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, sing and dance about it. People fight over it. And all people, everywhere and every day, need it.

The value water conveyed in Gorbachev's statement has been reflected in art and literature throughout the ages, in political debates and war stratagems, and in the sometimes desperate need to quench the thirst of a growing populace.

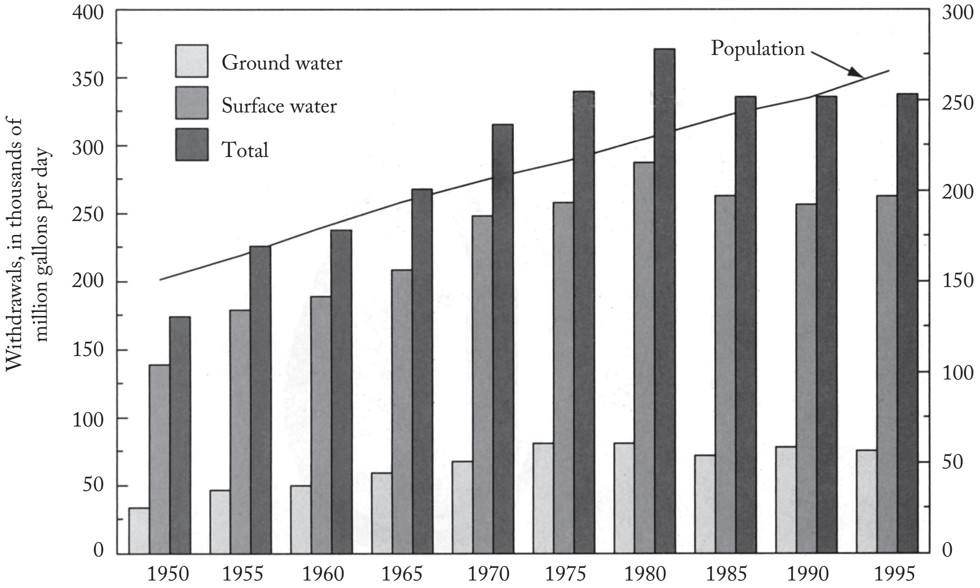
Water is the elixir of life; without it life is not possible. On earth the availability of clean water is uniquely tied to environmental sustainability, the history of human development, and the future of human aspirations. And the importance of water is not restricted to our planet. The search for life on other planets within our solar system or on exoplanets centers on water. It is possible that water will be the most important criterion for sustaining life on earth in the face of overexploitation, climate change, and projected population growth.

The number of people in the world without access to clean water is staggering. The United Nations World Water Development Report of 2020 estimated that water stress affects every continent except for Antarctica, and about 4 billion people face severe water scarcity at least one month each year. The report goes on to say that 1.6 billion people, almost a quarter of the earth's population, experience economic water shortage, that is, they do not have adequate infrastructure to obtain sufficient water. The report warns that over 52% of the world's population will live in water-stressed regions by 2050. Lack of water can foment political unrest, create social and economic upheaval, and be both a cause of, and a weapon in, conflict and war. While health figures do not do justice to individual suffering, and irreparable environmental damage is not adequately reflected in statistics, the numbers still can be staggering. Estimates vary greatly, but worldwide mortality attributed to lack of clean drinking water has been approximated at roughly 3.4 million preventable deaths per year, or just under 10,000 per day, most of which (about 2.2 million) are children. This does not even reflect deaths associated with lack of hand washing and resultant deaths with global pandemics such as COVID-19. Estimates are that approximately 5,000 children die each day from diarrheal fluid loss or lack of clean drinking water, or about one every 17 seconds. The United Nations and the World Health Organization have attributed water-related causes to about 80% of all diseases in the developing world. Inadequate water supply also is linked to food insecurity and diminished opportunity for energy development. Worldwide, agriculture accounts for about 70% of all water usage, with 20% for industry and 10% domestic consumption, but in industrialized nations over half of water usage is for industry. According to the United States Geological Survey water census (2018), 41% of recent water withdrawal in the US has been for thermoelectric power, while agriculture has accounted for 37%.

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 particularly in the ground. The US National Academies of Sciences, Engineering, and Medicine has determined that men living in a temperate climate require about 3.7 liters (L) (3.9 quarts [qt]) of fluid or potable water per day and women require 2.7 L (2.85 qt) 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. In contrast, a single cycle of an older flush toilet may use 19 L (5 gallons [gal]) of water. Some water conservation is occurring. In New York City the per capita water usage exceeded 1000 L (260 gal) daily several decades ago; now it is closer to 435 L (115 gal). Although the United States has had very high per capita use compared to the rest of the world, its water use is coming down. Australia has also shown a significant reduction. Even so, over the last 50 years freshwater withdrawal around the world has tripled. Demand for freshwater is estimated to be increasing at about 64 billion cubic meters (m^3) per year. Worldwide, the annual water consumption varies considerably country by country, according to the Organisation for Economic Co-operation and Development (2019). For example, per capita New Zealand is recorded as recently using over 2100 m^3 (550,000 gals) per year, whereas recent German consumption is under approximately 315 m^3(83,200 gal). Total freshwater withdrawals in the United States peaked in 1980 and have declined since then, with about 20% less withdrawal 35–40 years later despite increasing population (Figure 1.1). Water abstraction and consumption is important to people and healthy ecosystems, but it is also important to understand that water insufficiency can be driven by its uneven distribution in time and space, and poor management.

Although our intentions toward preserving the environment may be good, we sometimes act without full consideration of all possible outcomes. For example, in 1990, the United States 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



▲ **FIGURE 1.1**

Trends in fresh ground- and surface-water withdrawals and population in the United States. Source: US Geological Survey (2018).

have found that groundwater in some areas was 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.

More recently, the discovery of a suite of per- and polyfluoroalkyl substances (PFAS) in drinking water has been startling. The preponderance and persistence of this class of thousands of chemicals in water systems was largely unrecognized until the early 2000s, although some studies had indicated work-related exposure somewhat earlier. These compounds can be persistent and mobile in the environment, and can be found in a variety of products. Although being phased out by industry, these PFAS can be found in many products. The list includes some food packaging, chemicals used in stain-resistant furniture and carpets, water-repellent fabrics, fire-fighting materials, nonstick cookware, products used for many military and aerospace applications, and in a variety of automotive uses. By 2019, the United States identified over 600 locations in 43 States with high PFAS, including drinking water systems, and a report of the Nordic Council in 2019 estimated that health costs in Europe from PFAS exposure costs €52–84 billion (about $59–95 billion) annually. PFAS have been shown to hinder the body's natural hormones, boost cholesterol concentrations in the blood, weaken childhood immunity, cause development problems in fetuses, and increase cancer risks. The lesson to be learned here is that even the best of intentions can have unanticipated and extremely undesirable consequences on our limited water resources.

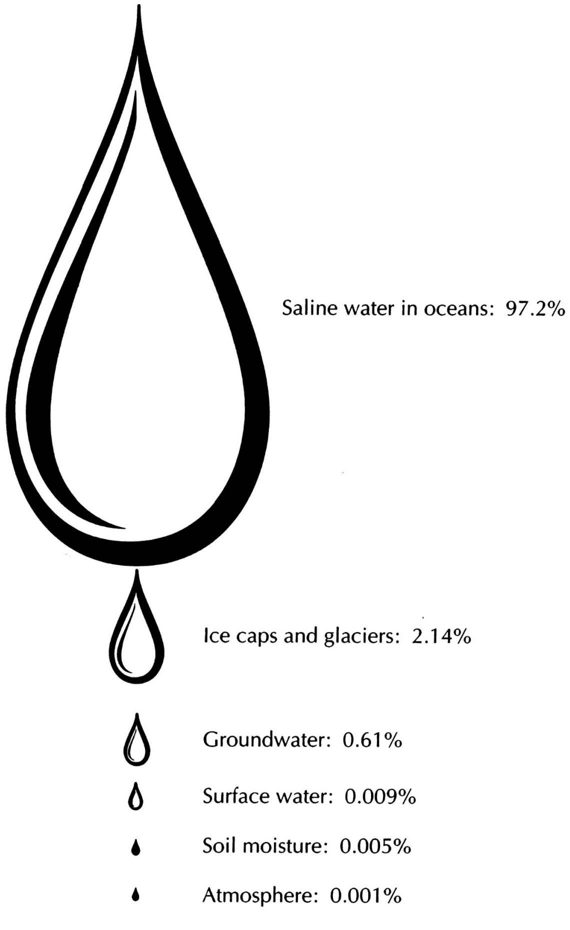
1.2 Hydrology and Hydrogeology

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, and prevailing wind directions. Running water and groundwater are geologic agents that help shape the land. The movement and chemistry of groundwater 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. Water management is complicated by the unequal distribution and lack of availability of water resources, and groundwater plays a significant role.

An account of the water supply of the world typically only deals with water in, on, or above the earth's crust, as this is the most usable supply to people and ecosystems. A broader look at the global water balance reveals that considerable amounts of inaccessible water may exist far below earth's surface. Deep, unreachable mantle water, particularly in the hydrous transition zone from about 410 to 660 km below earth's surface, is now thought to hold substantial amounts of water, although the quality of this water may be poor.

Estimates of potentially accessible and manageable water carry significant uncertainty. Approximations of earth's total water in, on, and above the earth's crust ranges from about 1300 to 1500 million km^3. Of that total, 1250–1465 million km^3 or 96–97.5% is considered saline ocean water (with 97.2% accepted by many), and the remaining 35–50 million km^3 (2.5–4%) of earth's water is, in large part, attributable to freshwater resources, although many saline lakes and groundwater brines exist globally (Filimonau and Barth 2016). These small percentages of "freshwater" are not always readily accessible—ice, snow, and glaciers account for 2–3% of crustal water in decreasing amounts due to climate change, while surface water and groundwater account for 0.5–1%. One estimate puts ice caps and glaciers holding 2.14%; groundwater to a depth of 13,000 feet (ft) (4000 meters [m]) accounting for 0.61% of the total; with soil moisture, 0.005%; freshwater 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). Atmospheric water has relatively short residence time and is a crucial part of the hydrologic cycle but represents a very small percentage of global water, estimated to be only 0.00093% of the accessible total, with even less (approximately 0.00004%) in the biosphere.



▲ FIGURE 1.2
Distribution of the world water supply. Information sources: Filimonau and Barth 2016; Shiklomanov 1993.

1.3 The Hydrologic Cycle

The cycle of life is intricately tied up with the cycle of water.

—Jacques-Yves Cousteau

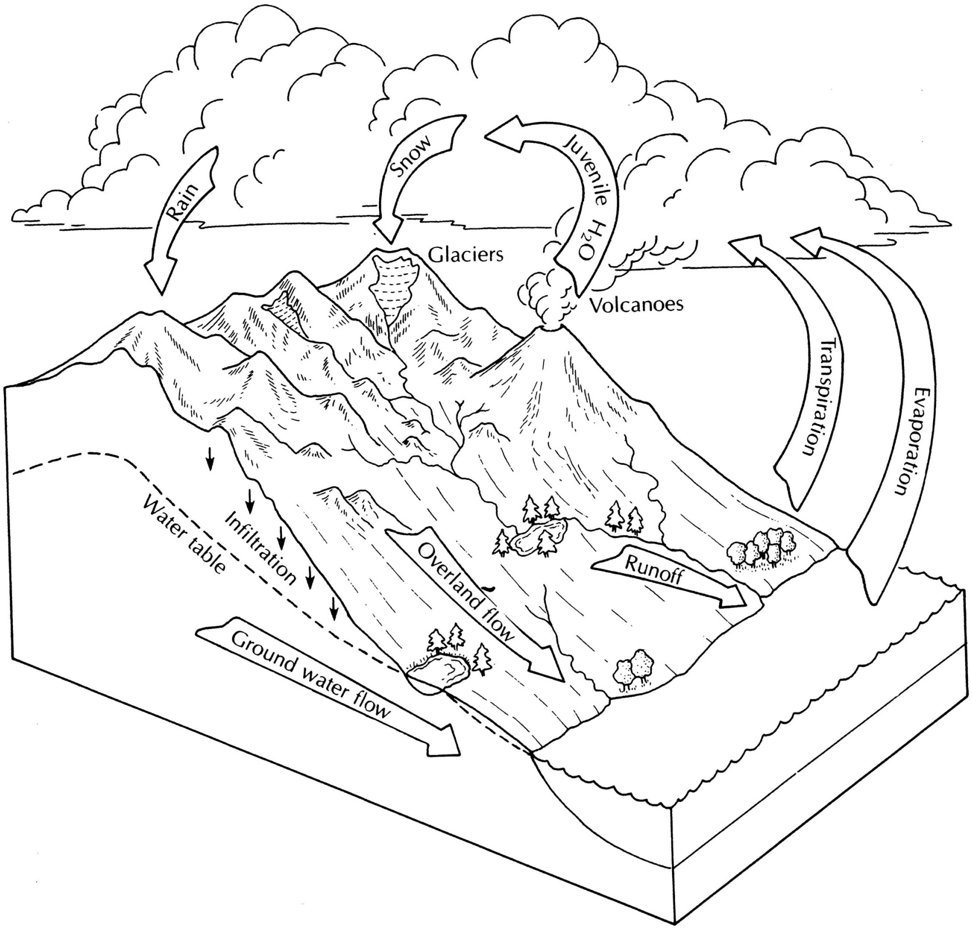
Only a small percentage of the world's total water supply is available to humans as freshwater. More than 98% of the available freshwater is groundwater, which far exceeds the volume of surface water. At any given time, less than 0.001% of the total water supply is in the atmosphere. However, atmospheric water circulates very rapidly, so that each year water falls in different amounts around the globe, ranging from more than 900 inches (2300 cm) annually in some parts of the tropics to less than 0.1 inch (in.)(0.25 centimeters [cm]) in certain deserts. In contrast, each year on average enough precipitation falls on the conterminous United States to cover it to a depth of 30 in. (75 cm) of water (US Geological Survey 2020). Of this amount, approximately 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. 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, typically immediately above the water table.

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 **groundwater**. It then moves as **groundwater 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). An **aquifer** is a geologic unit or strata that can yield a usable quantity of water to a well or to surface water.

Water flowing in a stream can come from overland flow or from groundwater that has seeped into the streambed. The groundwater 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**. There is an intermingling region in the banks of rivers, lakes, and wetlands where water can have the physical and chemical characteristics of both groundwater and surface water; this is called the **hyporheic zone**.

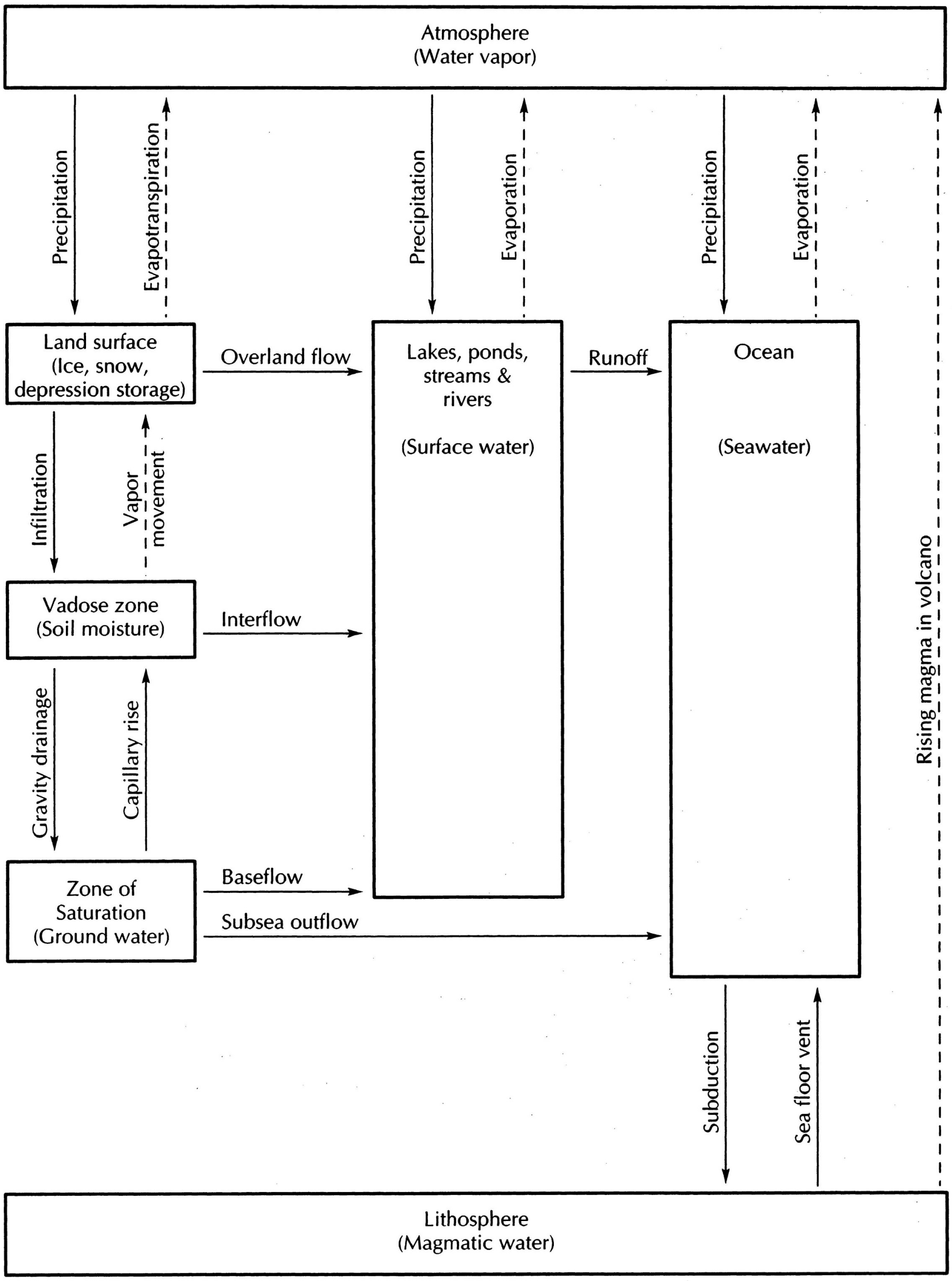


▲ **FIGURE 1.3**
The hydrologic cycle.

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 groundwater 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**.

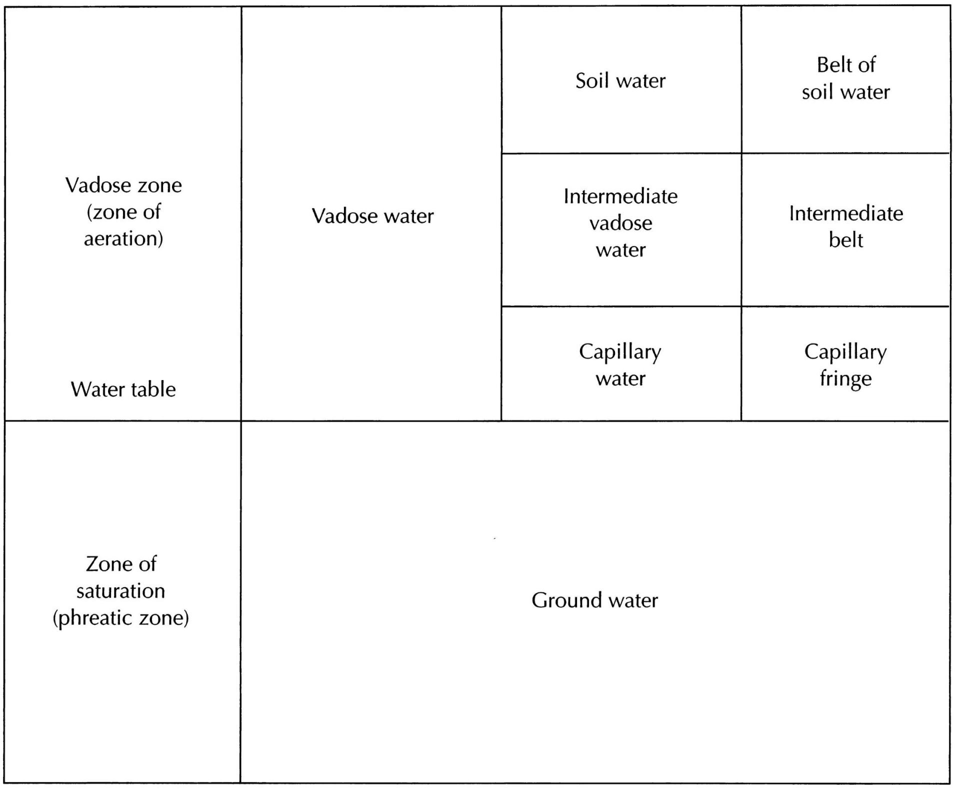
Magmatic water is contained within magmas deep in the crust. If the magma reaches the surface of the earth or the ocean floor, the magmatic water is added to the water in the hydrologic cycle. Steam seen in some volcanic eruptions is groundwater that comes into contact with the rising magma and is not 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.



▲ **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.



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.

1.4 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 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

$$H_v = 597.3 - 0.564T \quad \textbf{(1.1)}$$

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