# PREFACE

## BACKGROUND AND APPROACH

This book is about how we use water in the United States. Water is one of the most abundant, naturally occurring substances on Earth, and it is one substance we cannot live without. This life-or-death relationship is true for air as well as for water, but unlike air, water is unevenly distributed in space and time. Water is not always available where it is needed, when it is needed, or in the quantity or at the level of quality that is required. The spatial and temporal variabilities in both water supply and demand provide the most fundamental reasons for water planning and management. However, among the many other reasons for planning and managing water resources are minimizing conflicts between existing water users, accommodating new water uses or the expansion (contraction) of traditional uses, anticipating or responding to the changing values and priorities people place on different water uses, minimizing the environmental impacts associated with using water, and minimizing the impacts to society and the environment from the hydrologic hazards of floods and droughts. As more and more people make increasing demands on the limited water supplies, the importance of effective planning and management becomes ever more critical.

The principal goal of *Water Use, Management, and Planning in the United States* is to convey to students the breadth of the subject we call "water resources" and the depth of society's involvement in manipulating (managing) the hydrologic cycle. The only reasonable way to study water resources today is to use an interdisciplinary approach. Humans are now an important, if not the most important, agent of environmental change. The growing diversity in the type and scale of human impacts on water, land, and even the atmosphere is manifested as complex cascades of changes in the physical environment and human systems. Ideally, an interdisciplinary study incorporates the perspectives and knowledge of individual scientific disciplines and systematically integrates them to develop a "holistic" understanding of the topic. The more thoughtful the integration, the more successful the interdisciplinary approach. But the most successful interdisciplinary analysis goes beyond integration and achieves synergism among the individual elements.

What are the individual disciplines with a stake in water resources? There are many and they come from both the social sciences and the nonsocial (natural) sciences. From the social sciences, history, economics, geography, planning, law, and political science all contribute knowledge and a unique perspective about water as a natural resource. Among the natural (earth and life) sciences, hydrology, meteorology, geology, geomorphology, biology, and chemistry are providing distinct insights into the movement of water through the environment, how its physical and chemical properties are changed by human activities, and how those changes influence the structure and functioning of other natural systems, particularly ecosystems. Mathematics must also be included in our list because quantitative tools and analytical methods are fundamental to both social and natural scientists. As a geographer interested in water resources, I am accustomed to looking at the interaction between different factors in attempting to understand the patterns of water use and management. It would be presumptuous to say that geographers as a group are necessarily skilled in integrative analysis, but it is true that geographers are trained, and are therefore predisposed, to consider the interplay between the physical environment and human socioeconomic systems when trying to understand the use of natural resources. For me, an interdisciplinary approach to the topic of water seems only natural.

I thus wrote *Water Use, Management, and Planning in the United States* to satisfy my need for an interdisciplinary textbook, to use in an introductory, one-semester course on water resources. The presentation and material are targeted to an upper-division undergraduate and first-year graduate audience of students from a variety of disciplines within the natural and social sciences.

## ORGANIZATION

The first problem encountered in using an interdisciplinary approach is knowing where to begin. I start with hydrology in Chapter 1. This chapter is divided into several parts. One section discusses the components and processes that form the hydrologic cycle, or as I prefer to call it, the hydrologic system. Another section introduces and explores the concept of a water balance. A water balance is founded on the conservation of mass—water cannot be created or destroyed—so input to some "subsystem" must equal the output plus any change in water storage. This physical continuity makes a water balance one of the most important tools for planning and managing water. The final section considers the issue of global climate change and some potential impacts on hydrology and water resources. In addition to discussing hydrology, I use this chapter to define many of the terms encountered in the field of water resources. Like any other subject, water resources has distinctive, even unique, terms and concepts, and a challenge for any introductory book is to carefully define the terms that professionals in the field take for granted.

Chapter 2 is a review of the history of water resources in the United States. While tracing the historical developments in water resources, the chapter shows that our attitudes about water reflect broader, more general values in society. This chapter also provides a context and foundation for understanding many issues discussed in later chapters. The historical analysis begins in the early 19th century, when the only philosophy guiding the use of natural resources was that of exploitation, and water management meant water development. By the 20th century, the new philosophies of utilitarian conservation and natural resource preservation had emerged. As we move through the 20th century, we see that increases in environmental degradation coupled with fundamental changes in values gave rise to the environmental movement by the 1960s. In the past few decades, the emphasis on water development has largely given way to a focus on improved water management and "sustainable" water use. What is meant by sustainable use, however, is not always clear. Much of the history of water resources is a history of the activities of the federal government, largely because the federal government had the money to invest in large-scale water development, had a variety of incentives to do so, and possessed most of the technical expertise.

In Chapter 3 we turn our attention to water (quantity) law, which has been influenced by history and hydrology as well as several social institutions. This chapter begins with an examination of state laws for surface and groundwater use, followed by a look at federal laws affecting and controlling water use. The basic questions that underlie this chapter are who has the right to use water and how much are they allowed to use? The evolution of water law, and its reliance on precedent, gives this chapter a strong historical flavor.

Patterns of water use by source, water-use sector, and geographic region are the topics of the first part of Chapter 4. Because of the conventions and units used to report water data, it was logical to position this chapter after Chapter 1, where these terms are defined. The second part of this chapter covers geographic information systems (GIS). GIS technology is much more than methods and technologies for data storage, and I have provided a brief discussion of the basic types of GIS and their potential applications to resource analysis.

Chapter 5 deals with the discipline of economics. Because economic principles and analytical techniques are vitally important to resource decision making, this material is presented before the material on planning and decision making in Chapter 6. A number of the economic topics encountered throughout the book tend to be quantitative. Quantitative analyses in this and other chapters can be omitted if desired. However, quantitative material is always followed with a practical example to demonstrate its application. The major economic topics discussed include price theory, supply and demand, water markets, welfare economics, cost–benefit analysis, and environmental economics.

Chapter 6 addresses planning and management for water supply. The focus here is on water supply for the urban/domestic sector, but many of the principles can be applied to other water-use sectors. Where water supply planning was once limited almost exclusively to finding new sources of water, planners and managers are now turning to managing the demand. The second half of the chapter describes the rational planning model, some suggested (nonrational) modifications to the model of rational decision making, and the role of public participation in resource decision making.

Chapter 7 is a detailed examination of urban and agricultural water use—how water is used, how much is used, the spatial pattern of use by state, and the increasing role of conservation in balancing supply and demand. The section on urban water supply includes a discussion of drinking water quality and the 1996 amendments to the Safe Drinking Water Act and their influence on public water supply planning and management. Industrial water use is not covered, an omission necessary to design the text for a one-semester course.

Chapter 8 covers three instream water uses—hydropower, recreational uses, and instream uses for environmental purposes. Emphasis is primarily on the first two because environmental issues are considered again in Chapter 9 under the topic of water quality. Hydropower is a traditional water use that came of age during the first half of the 20th century. In contrast, the trend toward valuing water primarily for recreational uses emerged after World War II. The discussion of recreation focuses on the types of uses and levels of participation at facilities on federal public lands.

Chapter 9 discusses water quality and ecosystems. Some of the main topics addressed include water properties, a categorical treatment of water pollutants, point versus nonpoint sources of pollution and their control, water quality management under the Clean Water Act, and the status of aquatic species in the United States. Related resource issues are discussed within the framework of each pollutant category. A section on water quality management under the Clean Water Act considers the basic requirements and administration of the act, the emergence of nonpoint sources of pollution as the leading cause of water quality degradation, and the reemergence of the concept of basin-wide planning in the 1990s.

The final chapter examines the two hydrometeorological hazards—floods and droughts. This chapter uses the geographer's "human ecological" paradigm of natural hazards to explore how hazards are created through the interaction of a natural (physical) system and a socioeconomic system for resource use. Some of the more popular methods used to study the physical phenomena of these hazards and how society copes are discussed. As with water quality management, flood hazard mitigation strategies are evolving from the limited purpose of protecting people and property to a more holistic concern for natural floodplain uses and environmental protection.

## FEATURES OF THE BOOK

The book includes a wide variety of pedagogical features to enhance its usefulness. Important terms and concepts are italicized for emphasis. Numerous illustrations, 67 of which are original, and tables and many line, bar, and pie graphs present supporting details on water and related resources. I have also included 20 quantitative worked problems. The large diversity in the types of problems—from cost–benefit analysis in Chapter 5, to reservoir storage analysis and streamflow simulation in Chapter 6, to flood frequency analysis in Chapter 10—is yet another example of the interdisciplinary character of the subject. Each problem is worked in a step-by-step fashion that shows the types of data required and which is the appropriate equation(s) for solving the problem. I realize that quantitative analysis can be intimidating to some students and even some instructors, but in my experience even the most adamant "mathphobe" can gain additional insights by following the examples and doing similar types of exercises.

*Water Use, Management, and Planning in the United States* includes numerous focus boxes to present a variety of material. Within some boxes I have consolidated and highlighted important points and themes being discussed at length in the adjacent text. Some boxes provide examples of real water resource activities and programs relevant to that particular topic. Other boxes are used to frame water resource case studies, seven of which are included in the book. Some case studies are relatively brief and cover only one or two pages. Others, such as the story of how Los Angeles developed its water supply, are necessarily a bit longer. A unique feature of the water law chapter (Chapter 3) is the three exerpted court cases featuring important legal principles and precedents. Reading these decisions provides a taste of the nuances of legal analysis and judicial decision making.

Finally, I have included three appendixes containing common formulas for converting between different systems of units, a list of government sources of water data along with World Wide Web (WWW) addresses, and discount rate tables for cost–benefit analysis. Students are thus encouraged to browse the Web and discover important water resource sites.

Water resource management is in a state of change. Gone are the days when we could assume that there would always be a plentiful supply of water to meet our growing demands. Gone are the days when we sought to control rivers with impunity and by the force of our technology. Gone, too, are the days when we manipulated water resources for the benefit of "man" without regard to the impacts on natural systems and other species of life. This book is about how we use water in the United States, but every author must choose what to include and what to omit because it is impossible to cover everything. Every person has his or her own set of priority issues; mine are laid out here. This book owes its inspiration to all of the wonderful teachers I have had along the way. Anything that is commendable about the book, I owe to them. I alone take responsibility for the book's shortcomings.

*Stephen A. Thompson*

# 1

# THE PHYSICAL SYSTEM

- **Early Ideas about Hydrology**
- **Water Measurement**
- **The Hydrologic Cycle**
  - Water Storage
  - Water Cycling Processes
  - Precipitation
  - Infiltration and Soil Moisture
  - Runoff
  - Groundwater
- **Water Balance**
- **Climate Change**
  - Computer Simulation of Climate Change
  - Evidence for Climate Change

Water management involves manipulating the hydrologic cycle. This chapter focuses on the physical side of water management and is divided into five sections. The first section reviews early ideas about the hydrologic cycle. The second section covers water measurement including dimensions and units. The third section discusses the major components and processes of the hydrologic cycle. The fourth introduces the concept of a water balance. And the final section examines some water–related issues associated with the potential human alteration of the Earth's climate. Changes in established climate patterns could have profound impacts on water availability and established socioeconomic systems.

## EARLY IDEAS ABOUT HYDROLOGY

Every society has had to face the problems of water management, though some civilizations more than others. The Egyptians are credited with irrigation and flood control projects dating back to 5400 B.P. The ancient cities of Jericho, Babylon, and Carthage built water systems to provide drinking water to residents. The ancient Romans constructed water supply aqueducts, and they also built a closed sewage system which was more advanced than facilities available to millions of people in developing countries today (Gleick, 1993). Early societies accomplished amazing feats of water engineering even though they did not understand the hydrologic cycle or basic hydraulic principles. The Greek philosopher Aristotle thought water was held in a great underground sea and flowed up against gravity into the mountains, thence to flow back to the ocean. Plato's explanation for why water flowed down from the mountains was that cold temperatures converted air into water. These interesting but erroneous concepts about the hydrologic cycle persisted for centuries.

It was not until the Renaissance that accurate ideas about the hydrologic cycle emerged. Bernard Palissy (1510–1590) is credited with being the first person to state unequivocally that rivers have no source other than precipitation. Pierre Perault (1608–1680), a disbarred French lawyer turned natural scientist, undertook a field experiment to prove Palissy's assertion. Perault calculated a water balance for the Seine River basin and concluded that precipitation supplied more than enough water to the river. The noted English astronomer Sir Edmond Halley (1656–1742) was prompted to conduct studies on evaporation after condensation interfered with his telescopic observations. He determined that ocean evaporation was sufficient to replenish the rivers flowing back to the ocean.

The work of Renaissance scholars ushered in an age of hydrologic experimentation and quantification. But misperceptions about the hydrologic cycle persisted. In the United States the notion that local evaporation was primarily responsible for local precipitation was embodied in federal legislation. The Timber Culture Act of 1872 gave homesteaders in certain western states an additional quarter-section of land (160 acres) if they planted trees on 40 acres. It was thought the trees would increase transpiration and create more precipitation in the immediate area. It was also widely believed by the pioneers moving into the Great Plains in the second half of the 19th century that plowing the natural grassland vegetation caused the climate to become wetter. They were convinced that plowing increased evaporation from the soil, which in turn led to increased local rainfall. The fact was these settlers simply drew an incorrect conclusion from the cues offered by the naturally variable environment. Explorers to the western United States in the first half of the 18th century proclaimed it the "Great American Desert." This description is accurate for the extreme southwest, but the region of the central plains has a transitional climate fluctuating between semiarid and subhumid. It is characteristic in this type of climate to experience periods of abundant rainfall alternating with times of desiccating droughts. The early explorers saw this region during drought, while homesteaders in the 1870s and 1880s came during a wet spell. The homesteaders concluded that their action (plowing) modified the climate, causing it to become wetter. This conclusion was consonant with a prevailing cultural attitude that human transformations of natural landscapes were "improvements" over nature. By the 1890s drought returned to the region, forcing widespread abandonment of the land (Warrick and Bowden, 1981). The myth that "rain follows the plow" died in the dust of the deserted farms.

While the 19th–century notion that plowing caused the regional climate to become wetter is considered naive today, recent research has indicated there is a relationship, though poorly understood, between the persistence of droughts in the central United States and soil moisture levels (Oglesby and Erickson, 1989). It is unlikely that the early settlers influenced weather patterns in any significant way, but we should be careful in saying that their actions had absolutely no influence. The possible effect of land use on regional climate reemerged in the 1970s in the debate over the causes of *desertification* in the Sahel region of sub–Saharan Africa. Desertification is a complex process of vegetation and soil degradation believed to result through the interaction between land use and natural climate variation. One theory on desertification in the Sahel was that overgrazing had changed the reflectivity of the land surface, which through complex feedback processes changed local energy budgets and ultimately the amount of regional precipitation (Charney, 1975; Jackson and Idso, 1975). In other words it was thought that people in the Sahel had helped change the regional climate through abusive land use practices. Land–atmosphere feedback theories have been postulated to explain desertification in the overgrazed lands of the southwest United States as well (Schlesinger *et al.*, 1990). One of the most important questions facing scientists and decision makers today is whether human activities are changing climate on a global scale. We will return to this topic at the end of the chapter. It was not until the 1930s that the age of "modern" hydrology emerged based on scientific observation, experimentation, and theory. In the United States one of the leaders in the field was Robert Horton, who investigated a wide variety of hydrologic and geomorphic phenomena.

## WATER MEASUREMENT

The United States has resisted adopting the metric system of measurement so working with hydrologic and meteorologic data in the United States requires converting between conventional English and metric unit systems. This situation will continue into the foreseeable future. Even if the country adopted the metric system tomorrow the conversion problem would still exist because all of our historical data are in English units. Appendix 1 contains some useful conversion formulas.

Water has mass, it occupies space, it moves, it changes state, and it changes temperature. All of these physical properties are *dimensional quantities* that are measured using a system of units. Length ($L$) is a spatial dimension and is measured using units such as inches, feet, millimeters, centimeters, and meters. Volume is a three–dimensional quantity, $V = (L \times L \times L) = L^3$. Discharge ($Q$) is volume per

## EXAMPLE 1.1

Assume 0.5 inch of rain fell uniformly over an area of one square mile. Convert this into the equivalent volume of water. The 0.5 inch is a length ($L$) measurement. Area is (length × length) = $L^2$. The first step is to get all the data into the same units. A convenient English unit of length for this problem is feet.

Convert 0.5 inch into feet:

$$(0.5 \text{ in})(1 \text{ ft}/12 \text{ in}) = 0.0416 \text{ ft}.$$

Convert square miles into square feet:

$$(1 \text{ mi})(5280 \text{ ft/mi}) = 5280 \text{ ft}.$$

Thus one square mile is

$$(5280 \text{ ft})(5280 \text{ ft}) = 27{,}878{,}400 \text{ ft}^2.$$

Multiply the precipitation in feet by the area in square feet to get the volume of water in cubic feet:

$$(27{,}878{,}400 \text{ ft}^2)(0.0416 \text{ ft}) = 1{,}161{,}600 \text{ ft}^3.$$

In other words, 0.5 inch of rain over one square mile equals more than 1.16 *million* cubic feet of water. Since few people are familiar with cubic feet, convert cubic feet into gallons:

$$(1{,}161{,}600 \text{ ft}^3)(7.48 \text{ gal/ft}^3) = 8{,}688{,}768 \text{ gal of water}.$$

A small amount of rain can become a large volume of water when multiplied by area.

time, $Q = L^3/T$. Discharge is measured for streamflow and for wells. Example 1.1 demonstrates the relationship between precipitation measured in length and the equivalent volume of water over an area. Example 1.1 shows that relatively small amounts of rain can produce very large volumes of water. This is why storms that drop large amounts of rain over large areas produce devastating floods.

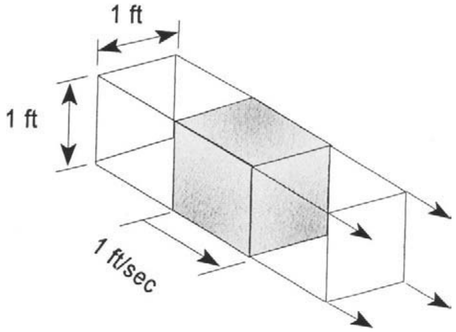

FIGURE 1.1 This figure shows that one cfs is produced by water moving at a velocity of one foot per second through a cross-sectional area of one square foot.

Discharge is a volume of water per unit of time ($L^3/T$). Discharge is calculated by multiplying water velocity ($L/T$) by the cross-sectional area ($L^2$) through

## EXAMPLE 1.2

In this example a stream flows into an empty reservoir. The reservoir is a square 600 feet on a side with vertical walls. The average discharge into the reservoir for a 24-hour period is 86 cfs. How deep is the water in the reservoir at the end of 24 hours?

First find the volume of water by multiplying average discharge by the time period. Since discharge is in ft$^3$/s, convert time (24 hours) into seconds:

$(86\ \text{ft}^3/\text{s})(60\ \text{s/min})(60\ \text{min/hr})(24\ \text{hr}) = 7{,}430{,}400\ \text{ft}^3$.

This again is the principle of getting all quantities into the same units. Next, find the area of the reservoir:

$(600\ \text{ft})(600\ \text{ft}) = 360{,}000\ \text{ft}^2$.

To find the water depth ($L$) divide the water volume ($L^3$) by reservoir area ($L^2$):

$7{,}430{,}400\ \text{ft}^3 / 360{,}000\ \text{ft}^2 = 20.64\ \text{ft}$.

The depth of water is 20.64 feet after 24 hours.

which the water flows. In the United States stream discharge is measured in cubic feet per second (ft$^3$/s or cfs). Again, most other countries use cubic meters per second (cms). Discharge from a pumping well is usually reported in gallons per minute. One cfs equals 7.48 gallons of water flowing past a reference point each second. Figure 1.1 is a sketch of discharge calculated as the water velocity times cross-sectional area. Discharge is converted into volume by multiplying the discharge by the time period over which it occurred. Example 1.2 demonstrates some relationships between discharge and volume.

From Examples 1.1 and 1.2 it is apparent that measuring water in cubic feet quickly produces very large numbers. It is cumbersome to work with so many digits so a larger unit for measuring water volume is frequently used. This unit is the *acre-foot.* An acre-foot is 1 acre covered to a depth of 1 foot. In case you did not learn this before, 1 acre equals 43,560 ft$^2$. An acre-foot thus equals 43,560 ft$^3$ of water. How many gallons of water are there in 1 acre-foot?

## THE HYDROLOGIC CYCLE

### WATER STORAGE

The hydrologic cycle is the continuous cycling of water from the oceans, to the atmosphere, down to the land surface, and back again to the oceans (Figure 1.2). Water is stored in the oceans, on the continents in lakes and rivers, underground in the soil and as groundwater, and in the atmosphere as water vapor and clouds. Approximately 96.5 percent of all the water on Earth is found in the oceans (Table 1.1). This water is too saline to be used directly for water supply. Desalinating seawater is possible but it is energy intensive and extremely expensive. Of the remaining water on Earth only 2.6 percent is freshwater on land. Most of this, about 1.74 percent, is stored as ice in continental glaciers and ice caps. The next

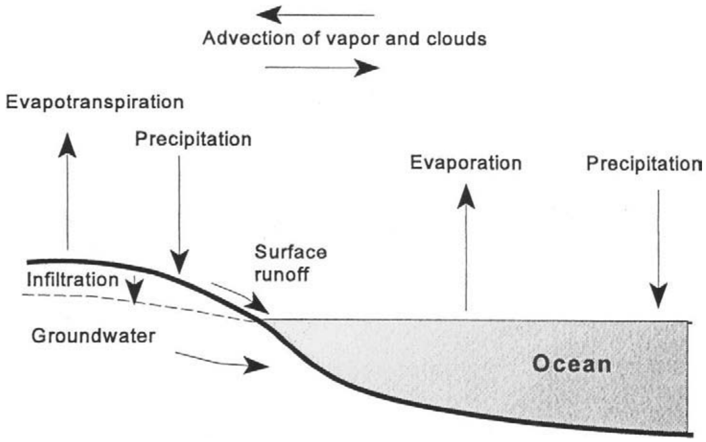

FIGURE 1.2 A simplified diagram of the global hydrologic cycle. (Source: Thompson, 1998)

largest store of freshwater (0.76 percent) is groundwater. Only about 0.27 percent of all the freshwater on Earth is found in lakes and rivers.

## WATER CYCLING PROCESSES

Hydrologic processes that transfer water from one storage location to another include *evaporation* and *evapotranspiration, precipitation, infiltration,* and *surface*

TABLE 1.1 Water Storage on Earth (Shiklomanov, 1993; Gardner, 1977)

| Location | Volume ($10^3$ kilometers) | Percentage of global reserves | | Average residence time |
|---|---|---|---|---|
| | | Total | Freshwater | |
| World oceans | 1,338,000 | 96.5 | — | 2600 years |
| Glaciers and permanent snow | 24,064 | 1.74 | 68.7 | 100–100,000 years |
| Groundwater | 23,400 | 1.70 | | 1–50,000 years |
| Fresh | 10,530 | 0.76 | 30.1 | |
| Saline | 12,870 | 0.94 | — | |
| Lakes | 176.4 | 0.013 | — | 100 years |
| Fresh | 91.0 | 0.007 | 0.26 | |
| Saline | 85.4 | 0.006 | — | |
| Soil | 16.5 | 0.001 | 0.05 | 3 months |
| Atmosphere | 12.9 | 0.001 | 0.04 | 10 days |
| Rivers | 2.12 | 0.0002 | 0.006 | 20 days |

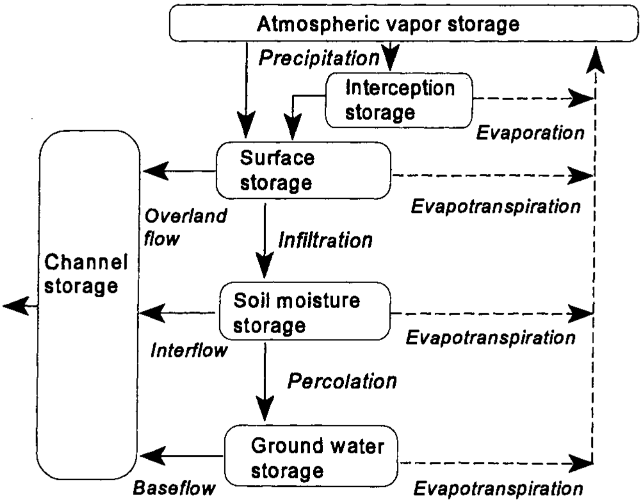

FIGURE 1.3 The basin-scale hydrologic system (cycle) showing water storages and processes. (Source: Thompson, 1998)

and *subsurface* runoff. Figure 1.3 shows some important hydrologic storages and processes at the scale of an individual *drainage basin.* A drainage basin is an area of land that drains water to a common outlet (Figure 1.4). In the United States drainage basins are also called *watersheds.* The line delineating a drainage basin is the drainage *divide.* A common simplification is to consider the drainage basin only in terms of surface runoff and to neglect groundwater flow. Groundwater usually flows into the stream channels of the basin but not necessarily. Since

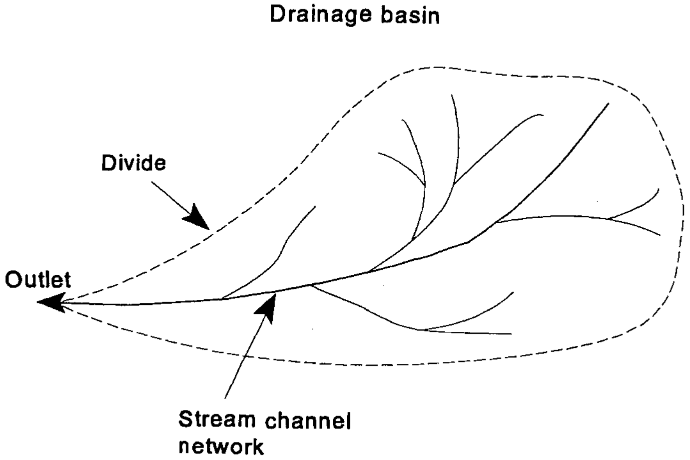

FIGURE 1.4 A drainage basin is an area of land that drains water to a common outlet. The drainage divide separates basins.

groundwater is not constrained by surface topography it can flow beneath surface–water divides.

Drainage basins are fundamental hydrological units because hydrologic processes connect upstream and downstream areas. Land–use change upstream can affect flooding downstream. Pollution in one part of the basin is carried by water to other parts of the basin. Water withdrawn and used upstream may be unavailable for use downstream. This physical connectivity is why drainage basins have long been considered ideal units for water–resource planning and management. Throughout history interest in unified river basin planning and management has waxed and waned. In general basin–wide planning has been more talk than reality, though there are significant exceptions such as the Tennessee Valley Authority. The reason is that political and administrative boundaries rarely coincide with natural basin boundaries, and decision makers are more responsive to political boundaries. It is interesting to note that in the 1960s Great Britain reorganized local political boundaries to correspond with drainage basin boundaries to facilitate water planning and management.

## Evaporation and Evapotranspiration

Evaporation is when energy is used to change the state of water from the liquid to the gaseous state, and the water molecules drift up into the atmosphere as water vapor. *Sublimation* is when water molecules change from the solid state (ice) directly into gas. Evaporation occurs from the surface of lakes, rivers, oceans, and wet soil. Since 71 percent of the Earth's surface is covered by ocean, most of the world's evaporation (about 86 percent of the total) occurs from the oceans. Transpiration is the same liquid–to–gas state change but it occurs as part of plant respiration, and the water molecules escape to the atmosphere through stomata on the leaves. On land, evaporation from wet soil and transpiration from plants are collectively called evapotranspiration. The hydrologic cycle starts with evaporation and evapotranspiration. The Sun, either directly as radiant energy or indirectly by warming the air, the water, or the soil, provides the energy for the change of state. When the Sun burns itself out some 12 billion years in the future, the hydrologic cycle will quickly come to a halt.

Three meteorological factors control the rate of evaporation—energy availability, wind speed and the humidity level of the overlying air. The more energy available, the faster the wind, or the drier the air, the greater the evaporation. You probably recognize these variables as the essential components of an electric hair drier. In addition to the meteorological factors, vegetative and soil factors affect the rate of evapotranspiration. In moving water from the surface to the atmosphere evapotranspiration plays an important role in cooling the Earth's surface. Solar energy basically does two things when it reaches the surface—it either heats the surface, or it evaportranspirates water. Energy used to evaporate and transpire water is unavailable for heating and vice versa. This is one reason why deserts are so hot; there is so little water available that virtually all of the Sun's energy goes into heating the land and the overlying air. (Ah, but it is a dry heat.) In humid climates with abundant vegetation and wet soil a significant amount of the Sun's energy is used for evapotranspiration. This keeps air temperatures lower but of course raises the humidity level of the air.

### Measurement of Evaporation and Evapotranspiration

Evaporation and evapotranspiration are measured or estimated using evaporation pans, lysimeters, and various formulas. Like precipitation, evaporation and evapotranspiration are measured as a depth of water, i.e., inches or millimeters. The most common type of evaporation pan used in the United States is the Class A Pan. The Class A Pan is galvanized steel with a diameter of 4 feet and a depth of 10 inches (Figure 1.5). One method of operating the pan is to fill it to a depth of 8 inches and then refill it when the water level drops to 7 inches. Measuring the water level in the pan on a daily basis gives an estimate of daily pan evaporation. Measurement errors can occur if birds drink from the pan, debris falls in, or water splashes out. The biggest problem with pans is that they evaporate more water than would a shallow lake located in the same area. This is because the pan sits above the ground and additional energy conducts through the walls of the pan into the water. This added energy increases pan evaporation relative to evaporation from a nearby lake. To correct for this upward bias a *pan coefficient* is used to lower the pan evaporation value so that it more closely represents evaporation from the lake. The most common value for the pan coefficient is 0.7. In other words, multiply the measured pan evaporation by 0.7 to get the estimated lake

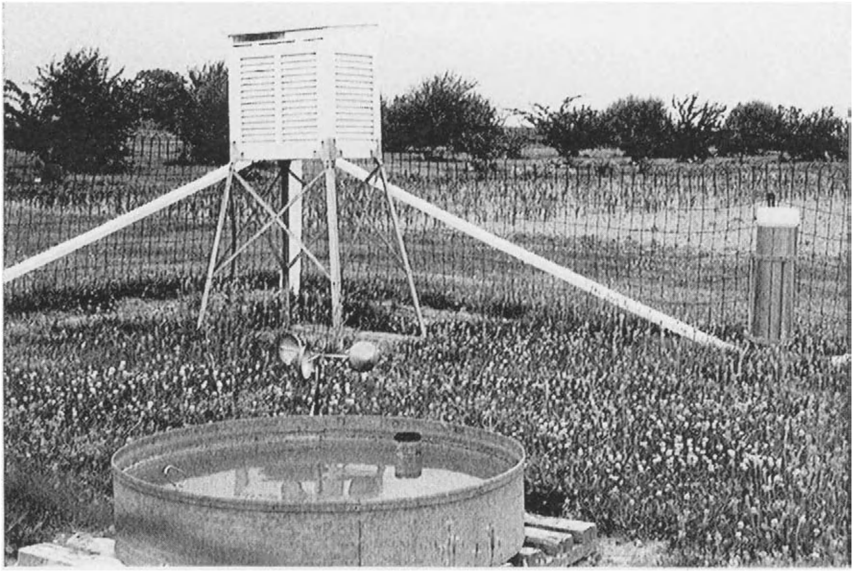

FIGURE 1.5 A Class A evaporation pan. The pan is exposed on a platform to allow air to flow under the pan. In the background is an instrument shelter and a nonrecording precipitation gauge.

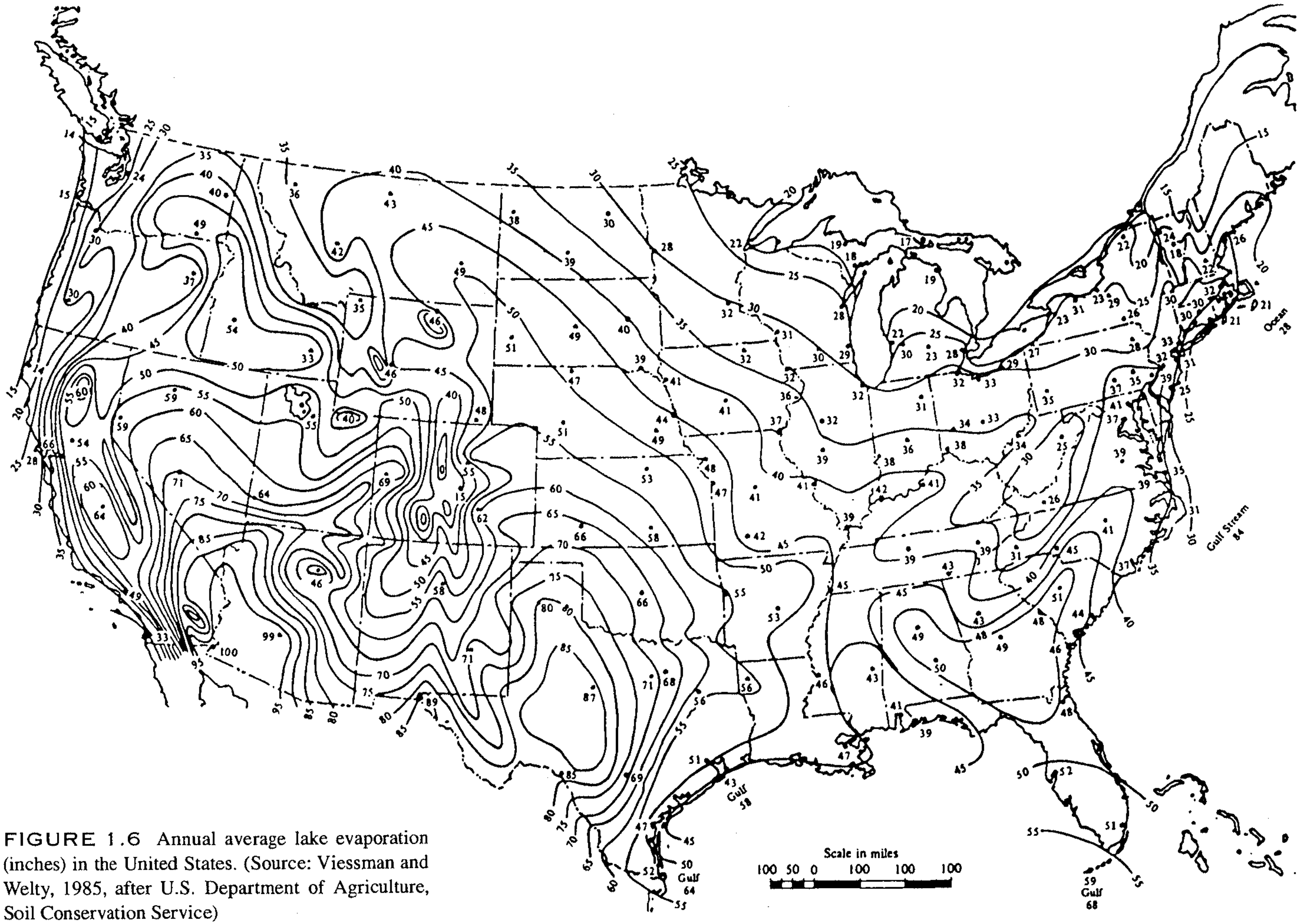

FIGURE 1.6 Annual average lake evaporation (inches) in the United States. (Source: Viessman and Welty, 1985, after U.S. Department of Agriculture, Soil Conservation Service)

evaporation. Typical values for daily evaporation are around one-tenth of an inch on a cool day, to more than a half an inch on a hot, windy day in the summer. Figure 1.6 shows isolines of annual average lake evaporation in the United States. Annual evaporation ranges from 20 inches per year in the Northeast and Northwest, to more than 100 inches per year along the lower Colorado River.

Lake evaporation is a major water management issue in the southwest United States. Water evaporated from reservoirs is lost from a water management point of view. In fact the single largest "use" of water in the entire state of New Mexico is evaporation from Elephant Butte reservoir on the Rio Grande. The only way to control evaporation is by covering the reservoir, which is feasible only for small municipal water supply reservoirs. No one has yet devised a way to reduce evaporation from large reservoirs.

*Lysimeters* are soil-filled tanks used to measure evapotranspiration. They are buried flush with the ground and planted to the same type of vegetation as that found in the surrounding area (Figure 1.7). There are two basic types of lysimeters—the nonweighing and the weighing lysimeter. The nonweighing lysimeter calculates evapotranspiration as the difference between the inputs of precipitation and irrigation water and any water draining out the bottom. This device does not measure soil moisture and should only be used in situations where the change in soil moisture is negligible. The weighing lysimeter uses a scale that allows the change in soil moisture storage to be determined from the change in the weight of the device.

A third way to estimate evaporation and evapotranspiration is by mathematical equations using meteorological data. The most sophisticated equations use solar energy, wind speed, and humidity as input variables. Penman's (1948) equation is

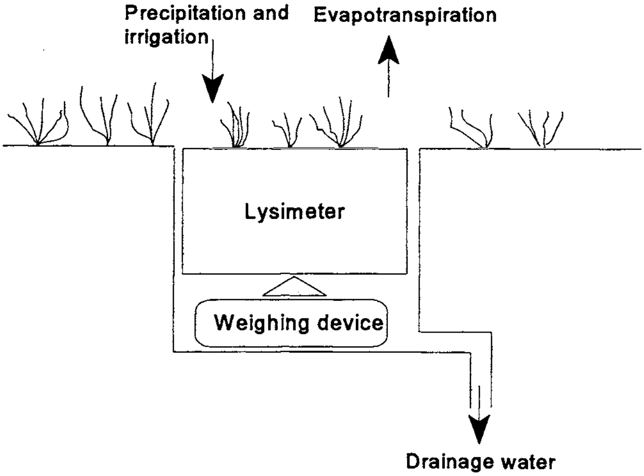

FIGURE 1.7 A simplified diagram of a weighing lysimeter for measuring evapotranspiration. (Source: Thompson, 1998)

of this type and is called a *combination equation* because it combines all three meteorological variables into one equation. The simplest equations are empirically derived and use only air temperature. The two most popular temperature-based evapotranspiration equations are Thornthwaite's equation (1948) and the Blaney–Criddle (Blaney, 1955) method. The trade-off is between the more accurate, but more data-intensive, combination equations versus the less accurate, but more data-forgiving temperature equations. Which equation you use depends upon the accuracy required and availability of meteorological data.

### Potential versus Actual Evapotranspiration

In hydrology and water resources the terms *potential* and *actual evapotranspiration* are frequently used. Potential evapotranspiration is the amount of evapotranspiration that would occur from a fully vegetated surface with adequate soil moisture at all times. In other words it is the rate of evapotranspiration limited only by the meteorological conditions and not limited in any way by vegetation or soil factors. Potential evapotranspiration is sometimes assumed to be the same as the rate of evaporation from a free water surface. As the soil becomes drier plants have a harder time extracting moisture, and their transpiration decreases. Thus the actual evapotranspiration may be lower than the potential value.

In the water-resources literature the term *consumptive use* is used as a synonym for either evaporation or evapotranspiration. Water that is consumed is no longer available for use by others. The distinction between the amount of water withdrawn for use and the amount consumed during use is important for water planning and management. For example, thermal (steam) electric power generation and irrigation agriculture both withdraw about the same amount of water on an annual basis in the United States. Using water to cool a power plant consumes about 3 percent of the water withdrawn, whereas irrigation agriculture consumes about 55 percent of the water withdrawn.

## PRECIPITATION

Precipitation is when water—in either liquid (rain) or solid form (snow)—returns from the atmosphere to the Earth's surface. There are other forms of precipitation including freezing rain, sleet, and hail, but for water management the most important forms are rain and snow. Precipitation is highly variable in space and time. Figure 1.8 shows *isohyets* of annual average precipitation in the continental United States. The spatial variability of precipitation is most extreme in the West, where annual precipitation varies from over 100 inches per year in parts of the Pacific Northwest to less than 4 inches per year in the desert Southwest. The extreme variability is due in large part to the mountainous topography. Westward flowing air masses are forced to rise up the windward (western) slopes of mountain ranges, resulting in adiabatic cooling, cloud formation, and precipitation. On the leeward (eastern) side the air descends, warms adiabatically by compression, and results in clear skies. The west-facing slopes receive more precipitation and are the source of most of the major streams and rivers in the western United States.

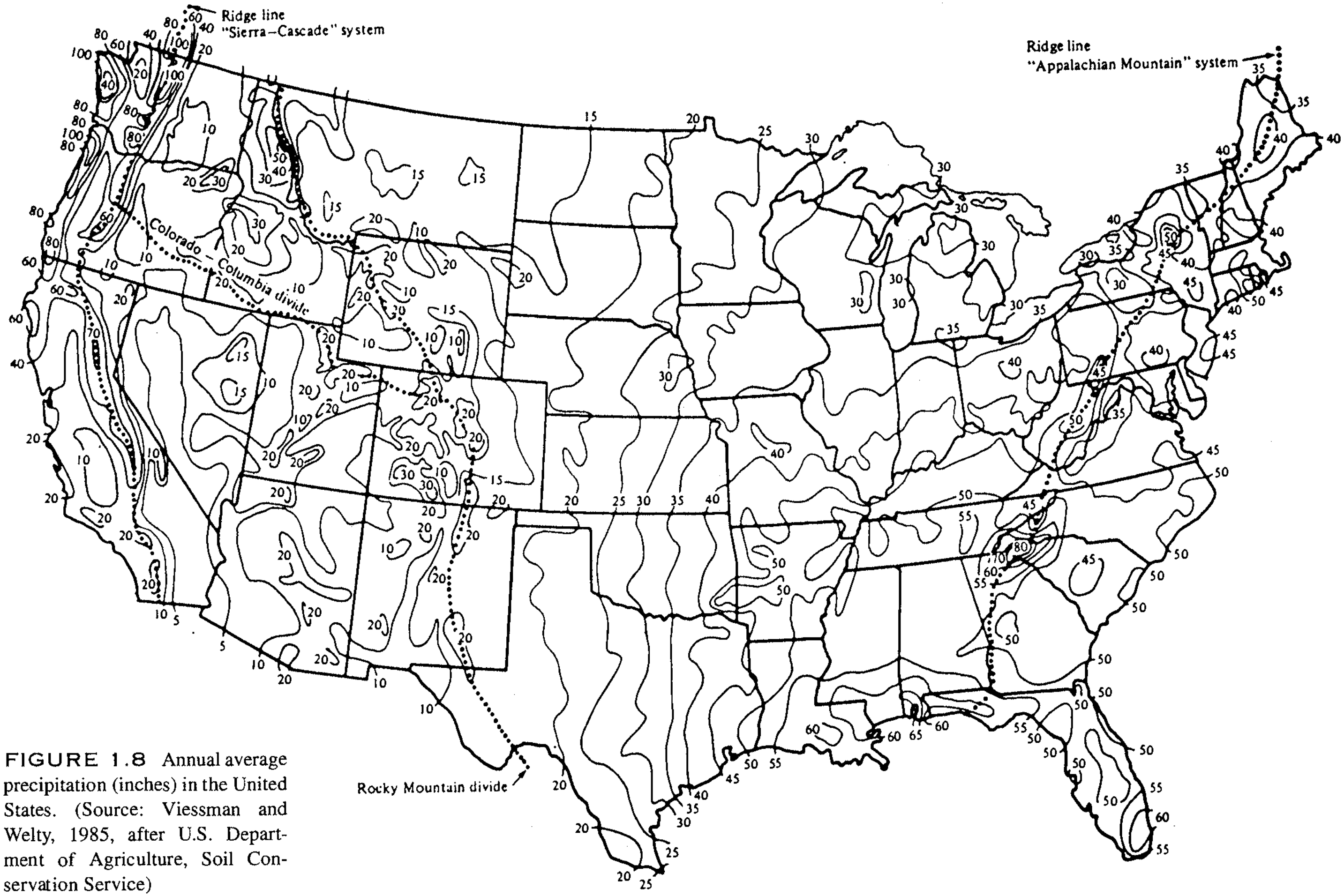

FIGURE 1.8 Annual average precipitation (inches) in the United States. (Source: Viessman and Welty, 1985, after U.S. Department of Agriculture, Soil Conservation Service)

Throughout the eastern United States annual precipitation is more spatially uniform. Annual values range from 60 to 70 inches per year in the South to around 40 inches per year in the Northeast. Again the more uniform pattern is largely because of the more gentle topography. The dividing line between the arid and semiarid West and the subhumid to humid East is conventionally taken as the 20-inch isohyet, because 20 inches of precipitation per year in the midlatitudes is about the minimum required to support trees. Where annual precipitation is between 10 and 20 inches per year, natural grassland vegetation dominates, and with less than 10 inches per year desert scrub prevails. The 20-inch isohyet is usually found near 98° W longitude. Looking at Figure 1.8 it is apparent that many locations in the western United States could have a water *quantity* problem. On the other hand the East has ample precipitation and water quantity has, at least until recently, not been as much of a problem. Many places in the East have long had water *quality* problems. We will address issues of water quantity and quality in later chapters.

Precipitation varies in time as well as space, though this is not apparent in Figure 1.8. Figure 1.9 shows graphs of monthly average precipitation at five locations in the United States. In southern New York precipitation is fairly evenly distributed throughout the year with every month having between 2.5 and 4 inches. In the winter much of it comes as snow. In south Florida precipitation is more seasonal with the wettest months in the late summer and fall. Wet summers and dry winters are typical of subtropical climates around the world. The fall maximum also reflects the importance of hurricanes and tropical storms. To the west in northcentral Colorado annual precipitation is less than half that of southern New York and Florida, and has a spring maximum. Much of the spring precipitation comes as snow. In the southwest desert of New Mexico the annual average precipitation is barely 10 inches per year, with half the total falling in just 3 months from July to September. This is the so-called summer monsoon season in the Southwest. Finally, the central coast of California is an example of a subtropical dry summer (also called mediterranean) climate where winters are wet and the summers are extremely dry. The water management problem here is that the time of greatest water demand (summer) is out-of-phase with the time of greatest water supply (winter). Hundreds of dams and reservoirs have been built to balance the timing of supply and demand by capturing the spring runoff for use later in the summer.

### Precipitation Measurement

Precipitation is measured using precipitation gauges (Figure 1.10). The standard National Weather Service gauge is a metal cylinder 8 inches in diameter. A removable funnel channels the water into a smaller inner cylinder. Precipitation is measured by inserting a graduated measuring stick into the inner cylinder. This is a *nonrecording gauge* because it measures only the total precipitation. Precipitation is recorded as a depth (length) of water. In the United States we measure precipitation in inches while most other countries use millimeters. *Recording*

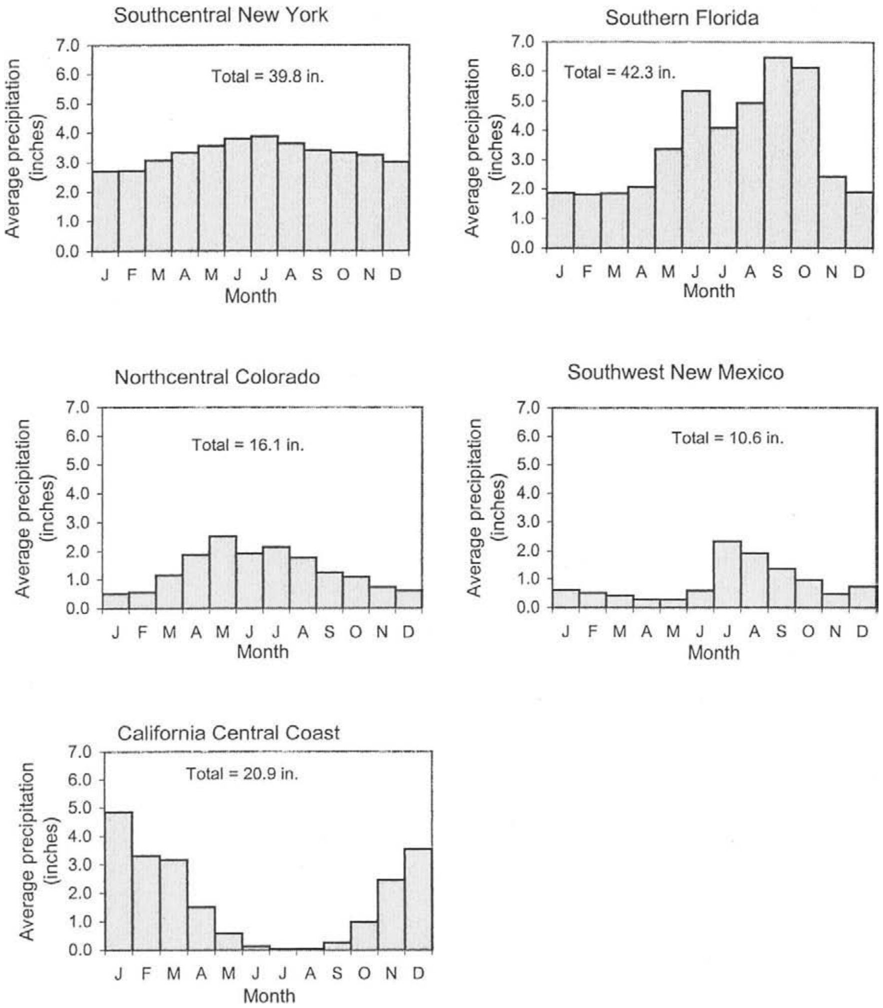

FIGURE 1.9 Monthly average precipitation for five locations in the United States.

*gauges* incrementally record precipitation during a storm. One type of recording gauge is the tipping–bucket gauge. Rain is directed into a small bucket having a capacity of 0.01 inch. When the bucket fills it overtips and brings a second bucket under the funnel. The tipping action triggers a data–recording device indicating that 0.01 inch of rain has fallen. The recording gauge generates a record of the time distribution of rainfall through a storm. A recording gauge thus gives values of rainfall *intensity,* e.g., inches per hour. Recording gauges are used in rainfall–runoff studies. A graph of precipitation or precipitation intensity versus time is called a *hyetograph* (Figure 1.11).