

defined channel such as a stream. Figure 1.3 shows the disposition of infiltration, depression storage, and surface runoff.

Water entering the ground may take several paths. Some may be directly evaporated if adequate transfer from the soil to the surface is maintained. This can easily occur where a high groundwater table (free water surface) is within the limits of capillary transport to the ground surface. Vegetation using soil moisture or groundwater directly can also transmit infiltrated water to the atmosphere by a process known as *transpiration*. Infiltrated water may likewise replenish soil moisture deficiencies and enter storage provided in groundwater reservoirs, which in turn maintain dry weather streamflow. Important bodies of groundwater are usually flowing so that infiltrated water reaching the saturated zone may be transported for considerable distances before it is discharged. Groundwater movement is subject, of course, to physical and geological constraints.

Water stored in depressions will eventually evaporate or infiltrate the ground surface. Surface runoff ultimately reaches minor channels (gullies, rivulets, and the like), flows to major streams and rivers, and finally reaches an ocean. Along the course of a stream, evaporation and infiltration can also occur.

The foregoing discussion suggests that the hydrologic cycle, while simple in concept, is actually exceedingly complex. Paths taken by particles of water precipitated in any area are numerous and varied before the sea is reached. The time scale may be on the order of seconds, minutes, days, or years.

A general hydrologic equation can be developed based on the processes illustrated in Figs. 1.2 and 1.3. Consider Fig. 1.4. In it, the hydrologic variables  $P$ ,  $E$ ,  $T$ ,  $R$ ,  $G$ , and  $I$  are as defined in Fig. 1.2. Subscripts  $s$  and  $g$  are introduced to denote vectors originating above and below the earth's surface, respectively. For example,  $R_g$  signifies groundwater flow that is effluent to a surface stream, and  $E_s$  represents evaporation from surface water bodies or other surface storage areas. Letter  $S$  stands for storage. The region under consideration specified as  $A$  has a lower boundary below which water will not be found. The upper boundary is the earth's surface. Vertical bounds are arbitrarily set as projections of the periphery of the region. Remembering that the water budget is a balance between inflows, outflows, and changes in storage, Fig. 1.4 can be translated into the following mathematical statements, where all values are given in units of volume per unit time:

1. Hydrologic budget above the surface

$$P + R_1 - R_2 + R_g - E_s - T_s - I = \Delta S_s \quad (1.1)$$

2. Hydrologic budget below the surface

$$I + G_1 - G_2 - R_g - E_g - T_g = \Delta S_g \quad (1.2)$$

3. Hydrologic budget for the earth [sum of Eqs. (1.2) and (1.3)]

$$P - (R_2 - R_1) - (E_s + E_g) - (T_s + T_g) - (G_2 - G_1) = \Delta(S_s + S_g) \quad (1.3)$$

## 1.5 APPLICATION OF THE HYDROLOGIC EQUATION

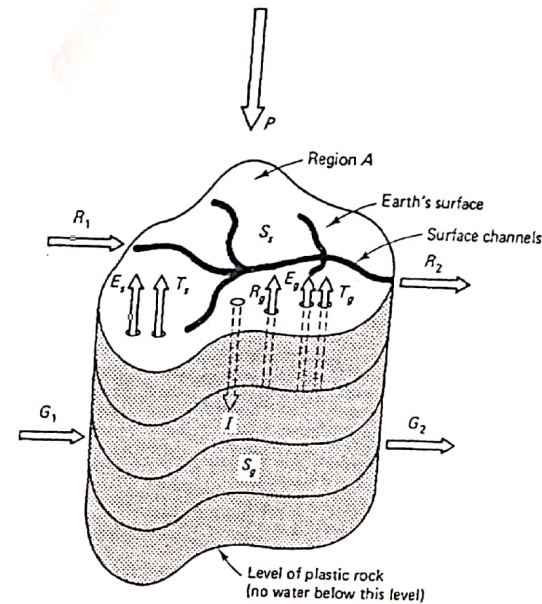


Figure 1.4 Regional hydrologic cycle.

If the subscripts are dropped from Eq. (1.3) so that letters without subscripts refer to total precipitation and net values of surface flow, underground flow, evaporation, transpiration, and storage, the hydrologic budget for a region can be written simply as

$$P - R - G - E - T = \Delta S \quad (1.4)$$

This is the basic equation of hydrology. For a simplified hydrologic system where terms  $G$ ,  $E$ , and  $T$  do not apply, Eq. (1.4) reduces to

$$P - R = \Delta S \quad (1.5)$$

Equation (1.4) is applicable to exercises of any degree of complexity and is therefore basic to the solution of all hydrologic problems.

## 1.5 APPLICATION OF THE HYDROLOGIC EQUATION

The difficulty in solving practical problems lies mainly in the inability to measure or estimate properly the various hydrologic equation terms. For local studies, reliable estimates often are made, but on a global scale quantification is usually crude. Precipitation is measured by rain or snow gauges located throughout an area. Surface flows can be measured using various devices such as weirs, flumes, velocity meters, and depth gauges located in the rivers and streams of the area.

Under good conditions these measurements are frequently 95% or more accurate, but large floods cannot be measured directly by current methods and data on such events are sorely needed. Soil moisture can be measured using neutron probes and gravimetric methods; infiltration can be determined locally by infiltrometers or estimated through the use of precipitation-runoff data. Areal estimates of soil moisture and infiltration are generally very crude, however. The extent and rate of movement of groundwater are usually exceedingly difficult to determine, and adequate data on quantities of groundwater are not always available. Knowledge of the geology of a region is essential for groundwater estimates if they are to be more than just rough guides. The determination of the quantities of water evaporated and transpired is also extremely difficult under the present state of development of the science. Most estimates of evapotranspiration are obtained by using evaporation pans, energy budgets, mass transfer methods, or empirical relations. A predicament inherent in the analysis of large drainage basins is the fact that rates of evaporation, transpiration, and groundwater movement are often highly heterogeneous.

The hydrologic equation is a useful tool; the reader should understand that it can be employed in various ways to estimate the magnitude and time distribution of hydrologic variables. An introductory example is given here, and others will be found throughout the book.

#### EXAMPLE 1.1

In a given year, a 10,000-mi<sup>2</sup> watershed received 20 in. of precipitation. The average rate of flow measured in the river draining the area was found to be 6000 cfs (cubic feet per second). Make a rough estimate of the combined amounts of water evaporated and transpired from the region during the year of record.

*Solution.* Beginning with the basic hydrologic equation

$$P - R - G - E - T = \Delta S \quad (1.4)$$

and since evaporation and transpiration can be combined,

$$ET = P - R - G - \Delta S \quad (1.6)$$

The term  $ET$  is the unknown to be evaluated and  $P$  and  $R$  are specified. The equation thus has five variables and three unknowns and cannot be solved without additional information.

In order to get a solution, two assumptions are made. First, since the drainage area is quite large (measured in hundreds of square miles), a presumption that the groundwater divide (boundary) follows the surface divide is probably reasonable. In this case the  $G$  component may be considered zero. The vector  $R_g$  exists but is included in  $R$ . The foregoing assumption is usually not valid for small areas and must therefore be used carefully. It is also presupposed that  $\Delta S = 0$ , thus implying that the groundwater reservoir volume has not changed during the year. For such short periods this assumption can be very inaccurate, even for well-watered

regions with balanced withdrawals and good recharge potentials. In areas where groundwater is being mined ( $\Delta S$  consistently negative), it would be an unreasonable supposition in many cases. Nevertheless, the assumption is made here for illustrative purposes and qualified by saying that records of water levels in the area have revealed an approximate constant in groundwater storage. Hydrology is not an exact science, and reasonable well-founded assumptions are required if practical problems are solved.

Using the simplifications just outlined, the working relation reduces to

$$ET = P - R$$

which can be solved directly. First, change  $R$  into inches per year so the units are compatible:

$$\begin{aligned} \frac{\text{ft}^3}{\text{sec}} \times \frac{1}{\text{area (in ft}^2\text{)}} \times \frac{\text{sec}}{\text{yr}} \times \frac{\text{in.}}{\text{ft}} &= R, \text{ in.} \\ R &= \frac{6000 \times 86,400 \times 365 \times 12}{10^4 \times (5280)^2} = 8.1 \text{ in.} \end{aligned}$$

Therefore,  $ET = 20 - 8.1 = 11.9 \text{ in./yr.}$

The amount of evapotranspiration for the year in question is estimated to be 11.9 in. This is admittedly a crude approximation but serves as a useful guide for water resources planning.

#### 1.6 HYDROLOGIC DATA

Hydrologic data are needed to describe precipitation; streamflows; evaporation; soil moisture; snow fields; sedimentation; transpiration; infiltration; water quality; air, soil, and water temperatures; and other variables or components of hydrologic systems. Sources of data are numerous, with the U.S. Geological Survey the primary one for streamflow and groundwater facts. The National Weather Service (NOAA or National Oceanic and Atmospheric Administration) is a major collector of meteorologic data. Many other federal, state, and local agencies and other organizations also compile hydrologic data. For a complete list of these organizations see Refs. 3 and 17.

#### 1.7 COMMON UNITS OF MEASUREMENT

Stream and river flows are usually recorded as cubic meters per second (m<sup>3</sup>/sec), cubic feet per second (cfs), or second-feet (sec-ft); groundwater flows and supply flows are commonly measured in gallons per minute, hour, or day (gpm, gph, gpd), or millions of gallons per day (mgd); flows used in agricul-



related to water storage are often expressed as acre-feet (acre-ft), acre-feet per unit time, inches (in.) or centimeters (cm) depth per unit time, or acre-inches per hour (acre-in./hr).

Volumes are often given as gallons, cubic feet, cubic meters, acre-feet, second-foot-days, and inches or centimeters. An acre-foot is equivalent to a volume of water 1 ft deep over 1 acre of land ( $43,560 \text{ ft}^3$ ). A second-foot-day (cfs-day, sfd) is the accumulated volume produced by a flow of 1 cfs in a 24-hr period. A second-foot-hour (cfs-hr) is the accumulated volume produced by a flow of 1 cfs in 1 hr. Inches or centimeters of depth relate to a volume equivalent to that many inches or centimeters of water over the area of concern.

Rainfall depths are usually recorded in inches or centimeters whereas rainfall rates are given in inches or centimeters per hour. Evaporation, transpiration, and infiltration rates are usually given as inches or centimeters depth per unit time. Some useful constants and tabulated values of several of the physical properties of water are given in Appendix B at the end of the book.

## 1.8 APPLICATION OF HYDROLOGY TO ENVIRONMENTAL PROBLEMS

It is true that humans cannot exist without water; it is also true that water, mismanaged, or during times of deficiency (droughts), or times of surplus (floods), can be life threatening. Furthermore, there is no aspect of environmental concern that does not relate in some way to water. Land, air, and water are all interrelated as are water and all life forms. Accordingly, the spectrum of issues requiring an understanding of hydrologic processes is almost unlimited.

As water becomes more scarce and as competition for its use expands, the need for improved water management will grow. And to provide water for the world's expanding population, new industrial developments, food production, recreational demands, and for the preservation and protection of natural systems and other purposes, it will become increasingly important for us to achieve a thorough understanding of the underlying hydrologic processes with which we must contend. This is the challenge to the water engineers, planners, policy-makers, lawyers, economists, and others who must guarantee that future generations will be served with an abundant water supply and that a quality environment will prevail.

It is with this perspective that this book was written. It is intended to provide a good foundation for those who are preparing to practice in the exciting and rewarding field of water management.

## PROBLEMS

- 1.1. Four inches of runoff result from a storm on a drainage area of  $50 \text{ mi}^2$ . Convert this amount to acre-feet and cubic meters.

## REFERENCES

- 1.2. Assume you are dealing with a vertical walled reservoir having a surface area of  $400,000 \text{ m}^2$  and that an inflow of  $0.5 \text{ m}^3/\text{sec}$  occurs. How many hours will it take to raise the reservoir level by 30 cm?
- 1.3. Consider that the storage existing in a river reach at a reference time is 15 acre-ft and at the same time the inflow to the reach is 500 cfs and the outflow from the reach is 650 cfs. One hour later, the inflow is 550 cfs and the outflow is 680 cfs. Find the change in storage during the hour in acre-feet and in cubic meters.
- 1.4. During a 24-hr time period, the inflow to a 500-acre vertical walled reservoir was 100 cfs. During the same interval evaporation was 1 in. Was there a rise or fall in surface water elevation? How much was it? Give the answer in inches.
- 1.5. The annual evaporation from a lake is 63 in. If the lake's surface area is 2000 acres, what would be the daily evaporation rate in acre-feet and in centimeters?
- 1.6. A flow of 10 cfs enters a  $1\text{-mi}^2$  vertical walled reservoir. Find the time required to raise the reservoir level by 6 in.
- 1.7. A drainage basin has an area of  $4571 \text{ mi}^2$ . If the average annual runoff is 5102 cfs and the average rainfall is 42.5 in., estimate the evapotranspiration losses for the area in 1 year. How reliable do you think this estimate is?
- 1.8. The storage in a reach of a river is 16.0 acre-ft at a given time. Determine the storage (acre-feet) 1 hr later if the average rates of inflow and outflow during the hour are 720 and 600 cfs, respectively.
- 1.9. Rain falls at an average intensity of 0.4 in./hr over a 600-acre area for 3 days. (a) Determine the average rate of rainfall in cubic feet per second; (b) determine the 3-day volume of rainfall in acre-feet; and (c) determine the 3-day volume of rainfall in inches of equivalent depth over the 600-acre area.
- 1.10. The evaporation rate from the surface of a 3650-acre lake is 100 acre-ft/day. Determine the depth change (feet) in the lake during a 365-day year if the inflow to the lake is 25.2 cfs. Is the change in lake depth an increase or a decrease?
- 1.11. One and one-half inches of runoff are equivalent to how many acre-feet if the drainage area is  $25 \text{ mi}^2$ ? (Note:  $1 \text{ acre} = 43,560 \text{ ft}^2$ .)
- 1.12. One-half inch of rain per day is equivalent to an average rate of how many cubic feet per second if the area is 500 acres?

## REFERENCES

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