Wanielista et al.

These benefits usually can be expressed in both quantitative and qualitative ways. To warrant investment, costs are generally required to be less than benefits expected. As a simple example, peak streamflow varies from year to year. Is it reasonable to provide protection against the very rare streamflow? The cost of this protection may be much greater than the losses from a flood. Thus, individuals in the planning area must be aware of the risk due to chance events associated with probable outcomes and incorporate economic considerations into the analysis.

1.2.2 Water Quality

The quality of water has become an issue of increasing importance over the years. Information in this text is primarily related to water pollution resulting from stormwater runoff and the prevention of pollution found in stormwaters. Many water quality issues are difficult to define in economic terms, such as the degradation of the recreational use of water and the loss of wildlife habitat due to pollution. Other water quality issues have a direct economic impact such as the quality of source waters that must be treated before being used.

Stormwater runoff has recently been identified as a significant source of pollutants in the natural environment (Yousef et al., 1985; Betson, 1978; Wanielista and Yousef, 1993). In many cases the water quality control systems can be easily adapted to include the prevention of pollutants in stormwater runoff. In some cases more costly measures need to be taken in the prevention of pollution.

1.3

WATER BUDGET AND MASS BALANCE

A water budget is an accounting of the volume of flow rate of water in all possible locations. Since density is constant it may be interpreted as a mass balance. One has to focus interest on a region and determine how the quantity of water in the region can be changed. The regional boundaries have to be determined across which water may move or be confined. Also, a time period must be specified.

A simple example of a budget is water from a parking lot. First, one must determine the surface boundaries of the parking lot that can contribute water to a collection point. The boundary may be defined on the surface as an imaginary line bordering the surface area from which precipitation can be accumulated and routed to some control point. At the control point, a decision may be made on the volume and rate of discharge. The control point can be an inlet grate at the lowest elevation of the parking lot. If the parking lot is constructed with curbs to contain the water on site, the boundary is easily determined. A parking lot is shown schematically in Figure 1.1. A water budget for that parking lot is helpful to present the concepts of a mass balance. Assume that all precipitation remains on the surface of the parking lot and is routed to a control point. This water volume is given the term rainfall excess. The rate at which rainfall excess appears over time at a discharge (control) point is called *runoff.* A water budget can be written in volume terms (mass balance):

$$\text{Inputs} - \text{outputs} \pm \text{accumulation} = 0$$

Water Budget

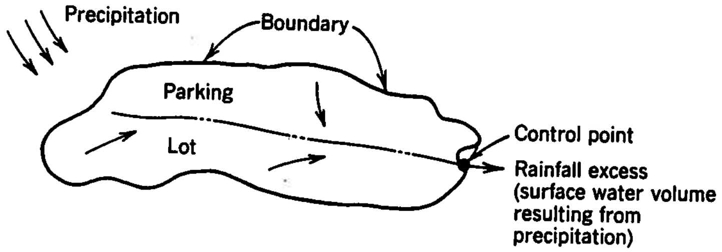

FIGURE 1.1 Parking lot water budget.

If water is not stored on the parking surface, the accumulation term is zero with input equal to precipitation and output equal to rainfall excess, or:

$$\text{Rainfall excess} = \text{volume of precipitation} \tag{1.1}$$

If precipitation is abstracted by depression storage in the parking lot, then the water budget in volume terms is altered as shown in Equation 1.2.

$$\text{Rainfall excess} = \text{precipitation} - \text{depression storage} \tag{1.2}$$

The complexity of a budget depends on the physical system and the ultimate use of the budget. Water budgets for large areas are complex with many parameters.

1.3.1 Global Water Budget

Available freshwater on earth comprises only about 3% of the total supply (Miller, 1986). More than 97% of the water on earth contains dissolved solids, which result in a salty taste. Direct human use and most industrial uses of salt water are possible only after some or most of the solids are removed. Other waters become unfit for municipal and industrial use when unwanted chemicals or rubbish are disposed of in them. Also biological changes can take place within the water resulting in a need for treatment before use.

Much of the freshwater is not readily available for use due to its remote locations. A majority of the freshwater (90%) is found in glaciers and polar ice caps. The small fraction of the total supply available for human consumption is estimated at about 4 billion billion liters. This is 400 million liters per person at a population of 10 billion people. It would appear then that water supply would not be a problem if remote sources could be made economically available and pollution could be minimized. Making water economically available is the major task.

On a global scale, the quantity of water is finite and its usable fraction can be altered (Wanielista et al., 1984). With a global water budget, one can establish water quality and quantity levels. Thus, the availability of water can be a matter of record, which provides responsible people with the database for decision making. This decision making can affect both water and land uses in a large region or a small council district. Useful storage must be monitored to ensure that there are no significant losses over time. When one of the inputs or outputs to the usable storage is significantly altered, changes will take place. These changes may be costly and life-styles may have to be altered. Life-style changes are already evident in places where usable water is in short supply. People must limit their consumption, which changes life-style.

As will be demonstrated in later chapters, the nature of the hydrologic problem becomes one of thoughtful consideration of the variability of water supply, i.e., distribution in time and space. Alterations of this naturally occurring scheme typically require engineering works and should be undertaken with extreme care. Complete hydrologic investigations will involve aspects of many other supporting sciences.

To illustrate variability of a hydrologic process, consider a flowing stream, creek, or river. Rarely, if ever, over a one-year period of observation can the observer record a constant flow rate or depth of flow. A listing of these flow rates over time or a graphical display (chart a figure) will more vividly illustrate the variability. These flow rates over time are called hydrographs. The hydrograph obtained from empirical observations or generated using computer programs is one of the more frequently used hydrologic descriptions. A plot of a hydrograph is shown as Figure 6.1.

Pollutants entering the water course directly affect water quality. These pollutants may be natural or man-induced. Quality also influences availability of supply depending on necessity. That is, it may be better to have poor or marginal quality water than none at all. Quality standards are important, even necessary, but not always sufficient to ensure adequate supplies.

1.3.2 Geographic Area Water Budgets

On a smaller scale, examples exist that indicate the value of a water budget. One such example is Amboseli National Park in southern Kenya. The park is located just north of Mount Kilimanjaro. Highly saline groundwater percolates from Kilimanjaro to Amboseli. The climate is arid, with on the average only 400 mm (16 in.) of rain per year.

After the early 1960s, the vegetation in the park changed along with the animal life that fed on the vegetation. What caused the changes? After an examination of a water budget for the area, it was found that precipitation on Kilimanjaro had increased dramatically. This caused groundwater levels to increase, which raised the groundwater levels beneath the lake beds in the National Park and caused a shift in the surface vegetation.

There are also examples of precipitation greatly exceeding watershed storage. In many cases, floods and subsequent damages can be reduced simply by storing water for release during dry periods. These examples show that simple water budgets are valuable and can provide operating guidelines for reservoir sizing.

Excessive precipitation is not the only problem. There are examples of too little precipitation causing drought conditions and rapid depletion of groundwater. This in turn causes an increased cost of water treatment. Subsidence, or sinkhole activity, has also been related to groundwater withdrawal. Possibly one of the most famous subsidence studies was conducted near Venice (Gambolati et al., 1974). Again, a water budget was used. The budget indicated a reduction in subsurface water occurred from pumping activities and could have caused the subsidence. Sinkhole activity in Florida and Texas has been related to groundwater withdrawal. A relatively complete history of sinkhole activities and related groundwater levels have been reported for the central Florida area. In the Houston–Galveston area, up to 3 m (9.8 ft) of subsidence has been noted and related to groundwater withdrawals. As pumps in wells remove great quantities of water from one of the United States most plentiful aquifers, about 1700 mi^2 of land has subsided. To prevent this subsidence, the source of water supply is being changed from groundwater to surface water and to practice more conservative use of water (*U.S. Water News*, 1985).

In Pennsylvania and other areas, increases in stormwater discharges to groundwaters were related to sinkhole activity. Possibly the increased volume and flow rates of stormwater being discharged to the aquifer caused dissolving of the limestone rock structure. Again, a water budget was used to estimate groundwater volume increases.

1.4

HYDROLOGIC CYCLE

The hydrologic cycle is a simplified accounting of the complex interactions of meteorological, biological, chemical, and geological phenomena. It is the movement of water from surface water, groundwater, and vegetation to the atmosphere and back to the earth in the form of precipitation. The transfer of water from plant tissues to the atmosphere is called transpiration. Plants absorb water from the soil through the root system. Rainfall can be abstracted onto vegetation, intentionally stored in ponds, be abstracted by depression storage (unintentional small volumes), infiltrated into the soil, or be available for discharge (rainfall excess). Rainfall that infiltrates into the soil, moves or percolates to the water table. Some of this groundwater may help recharge the aquifers. Some infiltrated waters may evaporate or flow in the direction of surface waters. This is a simplified accounting of a very dynamic process, shown in Figure 1.2.

Some surface water will remain after infiltration, abstraction by vegetation, and depression storage has been filled. An example of depression storage is a hole in pavement that stores water. This depression storage is different from the intentional design of surface storage ponds to reduce rainfall excess and runoff.

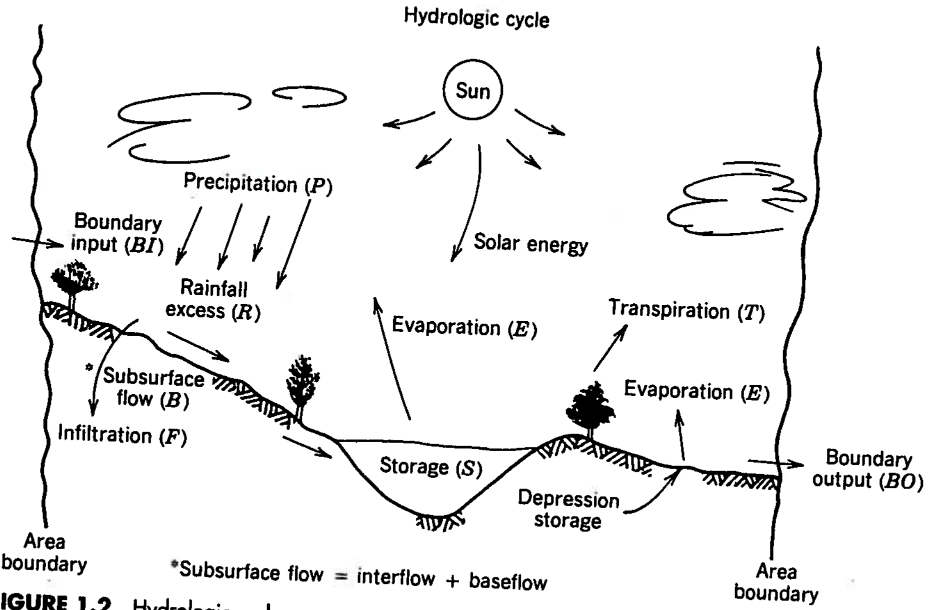

FIGURE 1.2 Hydrologic cycle.

1.4.1 The Hydrologic Cycle as a Mass Balance

Using a water budget to represent the hydrologic cycle, an equation to estimate surface water volumes can be developed. This equation is elementary but useful for surface water accounting where inputs and outputs vary with time. Volume units are used and time is fixed for most elementary applications of the water budget. All elements of the hydrologic cycle are dependent in some way on each other. A schematic representation of a pond is helpful to develop a mass balance equation, shown in Figure 1.3. All variables that cross the boundary must be accounted for in equation form. Rainfall excess is usually separated from surface storage to denote its significance in stormwater management studies. A mass balance equation for Figure 1.3 is

$$\text{Inputs} - \text{outputs} = \text{change in storage}$$

$$P + R + B - F - E - T = \Delta S \tag{1.3}$$

where ΔS = change in storage volume. A boundary transfer can be net human consumptive uses from surface volumes and/or groundwater volumes. In the water budget, volumes are measured in units of cubic meters, liters, acre-feet, cubic feet, gallons, or inches and centimeters over the watershed area. Also, a common way to express quantities of surface waters is in discharge units (volume per unit time). In the United States, data on discharge are available from the U.S. Geological Survey (USGS, all years) and other state and federal environmental departments. Other countries publish similar data.

It is often desired to perform a water budget for a specific time and on a specific watershed. The watershed of concern must be delineated to determine significant inputs over the time period. The time periods for analysis are chosen to be consistent with desired accuracy or storm event. Surface storage will change with time and is dependent on meteorological, geological, topographical, and human consumption factors.

1.4.2 Surface Water Supplies

One of the uses of the hydrologic cycle and a mass balance equation is in the estimation of surface storage. As an example, an area has an insufficient supply of water. Net input boundary exchanges may be increased by constructing reservoirs (water impoundments), restricting consumptives uses and importing water. Weather modifications are possible (however, not extensively used) for either increasing or decreasing precipitation. Geological surveys may indicate ways of directing subsurface runoff so

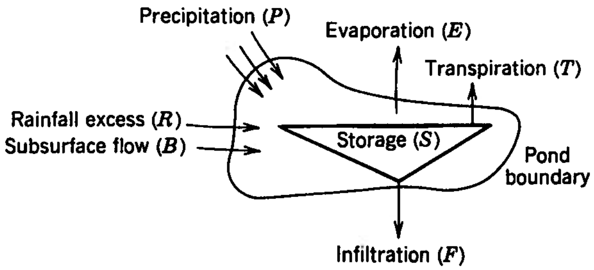

FIGURE 1.3 Schematic of hydrologic cycle.

that groundwater supplies are supplemented or transferred to surface waters. Thus, surface water inventories can be affected by various engineering projects. In addition to volume of inventory analysis of the hydrologic cycle, flow rates are important for establishing transport systems and quality degradation.

Storing and transferring a sufficient quantity of water from one location to another has been one of the major problems of society. Some questions related to surface storage and the hydrologic cycle are: What volume of water is stored in a surface reservoir and how does the volume change over time? What causes the water supply to be depleted or increased? How are the storage and releases managed?

Surface flows into a reservoir are necessary to maintain the beneficial uses of the reservoir. Adequate descriptions of these flow rates would be helpful to define flood levels, wildlife management, irrigation volumes, water-based recreation, and other social needs. Water quantity would be less of a problem if the source of usable, unpolluted water were located close to the users. Water is not always economically available at a particular location because rainfall quantities vary from one area to another. In addition, for one specific area, the stochastic (time-varying) aspects of rainfall must be considered for more reliable predictions of storage levels. Precipitation, evaporation, infiltration, and streamflows will be the material for latter chapters. The details for measurement and interpretation are necessary to use the basic mass balance of the hydrologic cycle as developed within this chapter.

1.4.3 Rainfall Excess

During a precipitation event, a mass balance of the total volume of rainfall onto and flow from an area is helpful to understand rainfall excess. Consider as variables the volume of precipitation P, rainfall excess R, infiltration F, evaporation E, transpiration T, and initial abstraction I_A. Initial abstraction is water intercepted by vegetation and stored in surface depressions. A mass balance of a simplified water budget for a fixed time period, considering negligible boundary transfers and no storage change, is written as

$$\text{Rainfall excess} = \text{precipitation} - \text{outputs}$$

$$R = P - E - T - F - I_A \tag{1.4}$$

Equation 1.4 is illustrated by the schematic in Figure 1.4.

In many locations it is difficult to separate evaporation and transpiration. Thus, the variables are considered together and most likely can be estimated as one value, identified as evapotranspiration (ET). For a short time period (hours-day) each of

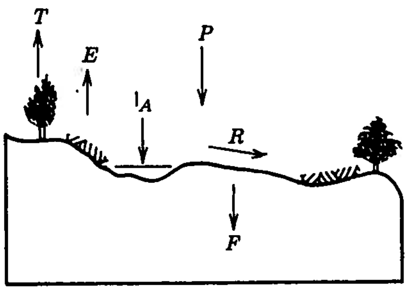

FIGURE 1.4 Water budget schematic.

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the above variables can be considered constant, and since evapotranspiration (ET) may be considered negligible during a precipitation event, Equation 1.4 is rewritten as

$$R = P - F - I_A \tag{1.5}$$

If the volume of infiltration and initial abstraction is proportional to the precipitation volume, the quantity of rainfall excess can be expressed as a fraction of precipitation:

$$R = CP \tag{1.6}$$

where C = runoff coefficient (dimensionless) such that $0 \leq C \leq 1$

The runoff coefficient, as defined here, is the ratio of rainfall excess to precipitation. The runoff coefficient can be determined from extensive rainfall and runoff studies, or from published values. In later chapters, the relationship of runoff (flow rate) to precipitation intensity and the runoff coefficient is developed.