McCuen, Hydrologic Analysis & Design

1.0 NOTATION

b_o	= model coefficient (intercept)	O	= outflow
b_1	= model coefficient (slope)	S	= storage
E	= evaporation	t	= time
I	= inflow	T	= temperature

1.1 HYDROLOGY: THE STUDY OF WATER

The word *hydrology* combines the Greek and word *hudōr*, which means "water," and the term *-logy*, which designates "a study of." It also has origins in the New Latin word *hydrologia*. More specifically, the general word *hydrology* refers to the scientific study of water and its properties, distribution, and effects on Earth's surface, soil, and atmosphere. The study of water can mean different things to different professions. To a chemist, a water molecule is a stable chemical bond of two atoms of hydrogen and one atom of oxygen; the chemist will be interested in the properties of water and its role in chemical reactions. The climatologist will be interested in the effect of the water stored in the soil and lakes on climatic processes. To those involved in the design of hydraulic machinery, the study of the properties of water will concentrate on the forces exerted by water in a dynamic state. To the mechanical engineer, the properties of water in the form of steam can be important. The ground water hydrologist will be interested in the movement of water in transporting pollutants. Even geographers and historians may be interested in water, at least in terms of how its availability and accessibility has shaped development and culture. However, our interest herein is in the narrow field of hydrologic engineering analysis and design. Engineering hydrology encompasses those aspects of hydrology that relate to the design and operation of engineering projects for the control and use of water. Aspects that relate to our nation's infrastructure are of special interest because of the decay of our infrastructure. Whereas the primary interest will be to the engineer, others, such as planners, environmentalists, water managers, and meteorologists, may find the knowledge of hydrologic engineering to be of interest.

Earth's atmosphere, oceans, ice masses, lakes, rivers, streams, and soil contain over 50 billion cubic feet of water. In spite of this abundance, problems are created by either too much or too little water at a given location; that is, problems are caused by the spatial variation of water. For example, people living in southern California and other areas of the arid southwest show concern over the lack of an inexpensive source of water supply. Problems also result from variations in the time distribution of water. An overabundance of water at one time or an undersupply at other times can have serious consequences to both agriculture and manufacturing, as well as inconveniencing the public. Occasional flooding is a problem to homeowners and to entire cities. Crops do not grow at the optimum rate when the soil is either too wet or too dry. Manufacturing operations require a consistent water supply over time for a variety of purposes, such as to provide cooling water and to assimilate wastes. Thus although Earth's total volume of water may be adequate to meet all needs, problems are created by variations in both the spatial and temporal distributions of water availability. Extreme problems, including life-threatening situations, can result from extreme variations in either the spatial or temporal distribution of water, or both.

Defn. Hydrology
Water Budget

In an attempt to overcome the problems created by these variations in the temporal and spatial variations in water availability, engineers and hydrologists attempt to make predictions of water availability. These predictions are used in the evaluation of alternative means of preventing or solving problems. A number of factors contribute to the ineffectiveness of these engineering designs. First, the occurrence of rainfall cannot be predicted with certainty. That is, it is not possible to predict exactly how much rain will occur in one time period (for example, day, month, year). The uncertainty of extreme variation in rainfall amounts is even greater than the uncertainty in the rainfall volumes occurring in the more frequent storm events. It is difficult to design engineering works that will control the water under all conditions of variation in both the time and spatial distribution. Second, even if we had perfect information, the cost of all of the worthwhile projects needed to provide the optimum availability of water is still prohibitive. Therefore, only the most efficient and necessary projects can be constructed. Third, hydrologic processes such as rainfall and runoff are very complex and a complete, unified theory of hydrology does not exist. Therefore, measurements of observed occurrences are used to supplement the scant theoretical understanding of hydrologic processes that exists. However, given the limited records of data, the accuracy of many engineering designs is less than we would like. These three factors (hydrologic uncertainty, economic limitations, and lack of theory and observed data) are just some of the reasons that we cannot provide solutions to all problems created by undesirable variations in the spatial and temporal distributions of water.

In spite of the inherent uncertainty in precipitation, the economic constraints, and the bounds on our theoretical understanding of hydrometeorological processes, solutions to the problems that are created by the temporal and spatial variations in water availability must be provided. Estimates of hydrologic quantities such as streamflow are required as input to engineering designs, which represent the engineer's attempt to solve the problem. All engineering designs should, at the minimum, be rational. An understanding of the physical processes is a necessary prerequisite to the development of rational designs.

1.2 THE HYDROLOGIC CYCLE

The physical processes controlling the distribution and movement of water are best understood in terms of the hydrologic cycle. Although there is no real beginning or ending point of the hydrologic cycle, we can begin the discussion with precipitation. For the purposes of this discussion, we will assume that precipitation consists of rainfall and snowfall. A schematic of the hydrologic cycle for a natural environment is shown in Figure 1–1. Rain falling on Earth may enter a water body directly, travel over the land surface from the point of impact to a watercourse, or infiltrate into the ground. Some rain is intercepted by vegetation; the intercepted water is temporarily stored on the vegetation until it evaporates back to the atmosphere. Some rain is stored in surface depressions, with almost all of the depression storage infiltrating into the ground. Water stored in depressions, water intercepted by vegetation, and water that infiltrates into the soil during the early part of a storm represent the initial losses. The loss is water that does not appear as runoff during or immediately following a rainfall event. Water entering the upland streams travels to increasingly larger rivers and then to the seas and oceans. The water that infiltrates into the ground may percolate to the water table or

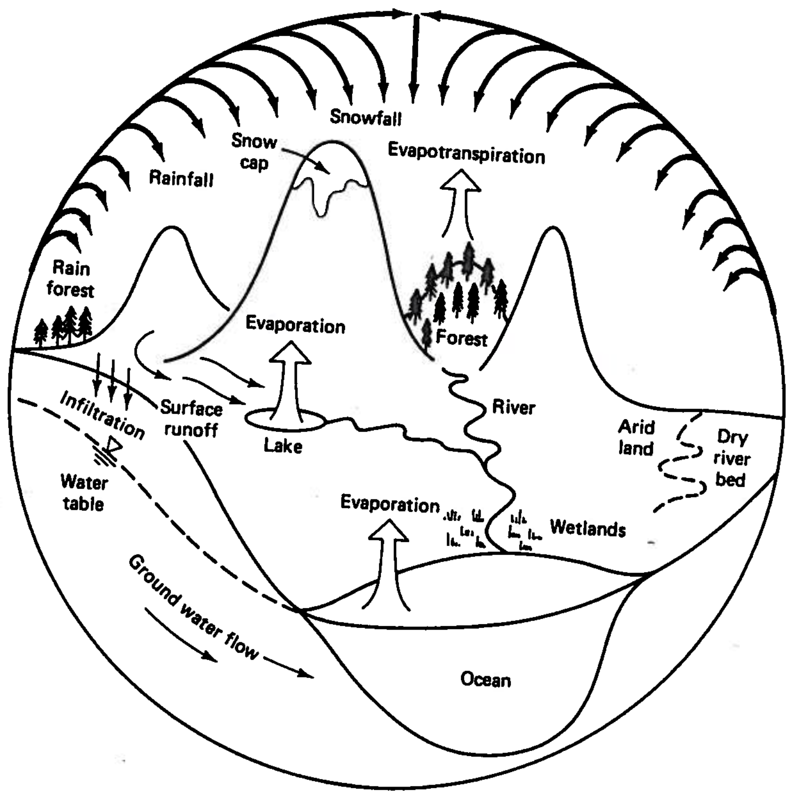

FIGURE 1–1 Hydrologic cycle of a natural environment.

travel in the unsaturated zone until it reappears as surface flow. The amount of water stored in the soil determines, in part, the amount of rain that will infiltrate during the next storm event. Water stored in lakes, seas, and oceans evaporates back to the atmosphere, where it completes the cycle and is available for rainfall. Water also evaporates from soil devoid of vegetation. Rain that falls on vegetated surfaces may be intercepted; however, after the storage that is available for interception is filled, the water will immediately fall from the plant surfaces to the ground and infiltrate into the soil in a similar manner as the water falling on bare ground infiltrates. Some of the water stored in the soil near plants is taken up by the roots of the vegetation, and subsequently passed back to the atmosphere from the leaves of the plants; this process is called *transpiration.*

Although it may appear that the hydrologic cycle of a natural environment is static, it is important to recognize that the landscape is constantly undergoing a transformation. High-intensity storms cause erosion of the land surface. Flood runoff from large-volume storms causes bankfull and high-velocity flows in streams with the potential for large amounts of channel erosion. During periods of extreme drought the perimeter of desert lands may increase. Forest fires caused either by natural means such as electrical storms or by the carelessness of human beings cause significant decreases in the available storage and decrease the surface roughness, both of which contribute to increases in surface runoff rates and volumes, as well as surface erosion. When mud flows are a potential problem, forest fires consume the vegetation, which contributes significantly to the increased production of debris. In many parts of the world, the largest floods result from the rapid melting of snow; such events can be as devastating as floods produced by large rainfall events. Flooding accompanying hurricanes and monsoons can also cause significant changes to the landscape, which by itself affects runoff rates and volumes from storms occurring long after the hurricane or monsoon. In summary, even in a natural environment, rainfall and runoff cause major changes in the watershed.

As the population of the world has increased, changes to the land have often been significant, with major changes to the runoff characteristics of a watershed as a result. Land clearing for agricultural development increases the amount of exposed soil, with obvious decreases in the protective covering of the natural vegetation. This loss of protective covering decreases the potential for infiltration, increases surface runoff, and can result in significant soil losses. Over the last two centuries, urbanization has caused significant changes to the landscape surrounding these urban centers. Urbanization has had significant effects on the processes of the hydrologic cycle for watersheds subject to the urban development. Clearing of the land has reduced the vegetation and therefore the availability of interception storage; grading of land surfaces reduces the available volume of depression storage. Impervious surfaces reduce the potential for infiltration and the resulting recharge of ground water storage. Impervious surfaces are also less rough than the natural surfaces and thus offer less resistance to the runoff; this change in roughness can increase runoff velocities and surface erosion. These changes to the processes of the hydrologic cycle, which are shown schematically in Figure 1–2, cause significant changes in runoff characteristics. The reduced storage results in increased volumes of surface runoff. The reduced surface roughness decreases the travel time of runoff. The reductions in both storage and travel time result in increased peak rates of runoff, which increase both flood damages due to overbank flows and channel erosion.

In an attempt to compensate for the lost natural storage, many localities require the replacement of the lost natural storage with human-made storage. While the storm water detention basin is the most frequently used method of storm water management, other methods are used, such as infiltration pits, rooftop and parking lot storage, and porous pavement. These engineering works do not always return the runoff characteristics to those that existed in the natural environment. In fact, poorly conceived methods of control have, in some cases, made flood runoff conditions worse.

1.3 HYDROLOGIC DESIGNS

The average American drives about twenty-five miles per day. While many of these miles involve travel on the same route, say to or from school or a job, the individual traveler will encounter a surprisingly large number of engineering designs where hydrologic analyses were required. In fact, hydrology was considered in the design of the very twenty-five miles of highway covered in an average day. Failure to consider drainage of the highway subbase can lead to premature failure of the highway. In addition to subbase design, hydrologic analyses

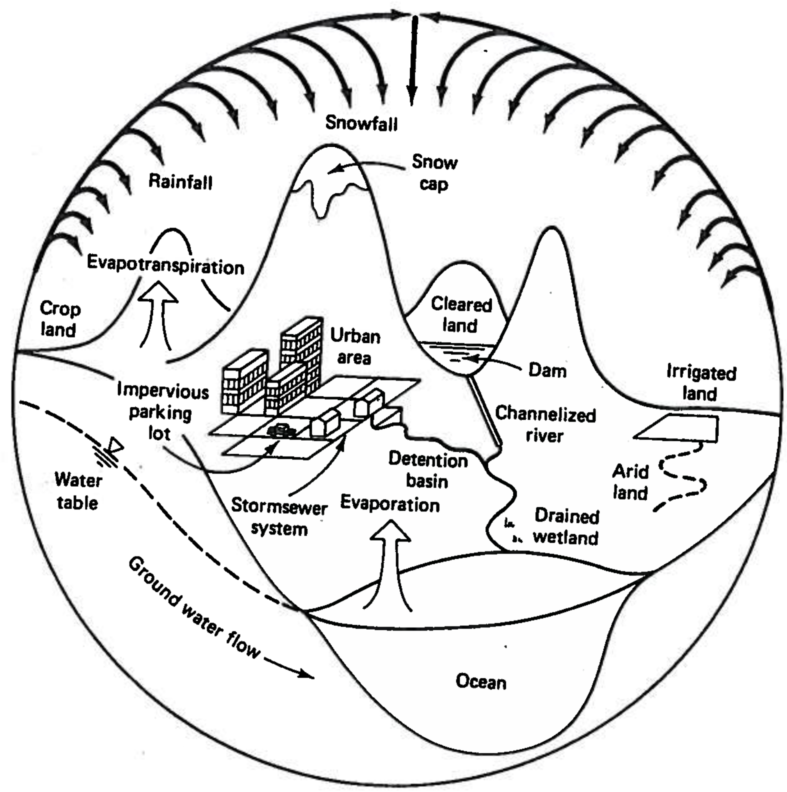

FIGURE 1–2 Hydrologic cycle of a developed environment.

are required for the design of culverts (for example, a pipe that crosses under a road or embankment), surface drainage inlets, and bridges that cross over rivers and streams. It should be evident that those involved in highway design must understand the basic concepts of hydrologic analysis since the design of every mile of highway requires consideration of the fundamental concepts of hydrology. Other elements of transportation systems require hydrologic analyses. Those involved in the design of parking lots, airport runways and aprons, rapid mass transit lines, and train rights-of-way must give just as much consideration to the proper drainage of storm runoff as those involved in the design of highways.

Those involved in the design of transportation facilities are not the only ones who must consider the natural passage of water resulting from storm events. Anyone involved in land development and the construction of homes, as well as commercial, industrial, and institutional buildings, must give consideration to storm runoff. Obviously, those involved in home design must provide gutters and down spouts. Buildings in commercial and industrial developments also require roof drainage.

There are many other hydrologic analyses required in building construction. When clearing land for development, it is important to provide sediment control facilities to ensure that eroded soil does not enter into waterways and wetlands. Sediment control depends on the area of the land being cleared, the amount of rainfall that can be expected during the period where the soil will be exposed to rainfall impact, and site characteristics such as the slope and soil type. In addition to hydrologic considerations during the land development stage, site development must consider drainage patterns after development.

Site development usually results in significant increases in impervious surfaces, which results in increased surface runoff rates and volumes. In many localities, storm water control facilities are required. In the upper reaches of a site, swales can be used to move water away from buildings and transportation facilities. Concentrated runoff from swales may enter gutters and drainage ditches along roadways where the runoff may drain into highway inlets or small streams. At many sites where land development has resulted in large amounts of imperviousness, on-site detention basins may be required to control the increased runoff. The design of storm water detention basins requires knowledge of routing of water through the hydraulic outlet structure, as well as knowledge about surface runoff into the detention basin. The design must consider meteorological factors, geomorphological factors, and the economic value of the land, as well as human value considerations such as aesthetic and public safety aspects of the design. The design of a storm water detention basin should also consider the possible effects of inadequate maintenance of the facility.

The hydrologic designs discussed in the preceding paragraphs are based primarily on rainfall and the resulting surface runoff. Dams and the water stored in the reservoirs behind the dams provide many benefits, such as power generation, recreation, flood control, irrigation, and the maintenance of low flows for water quality control. In addition to estimating the volume of inflow into the reservoir, dam design requires assessment of the evaporation losses from the reservoir. For reservoirs with large surface areas, evaporation losses can be significant. Failure to consider evaporation losses during the design could result in overestimating the water that would be available for the purposes stated above. Thus, failure to understand the processes of the hydrologic cycle may render the design inadequate.

1.4 ANALYSIS VERSUS SYNTHESIS

Like most of the basic sciences, hydrology requires both analysis and synthesis to use the fundamental concepts in the solution of engineering problems. The word *analysis* is derived from the Greek word *analusis*, which means "a releasing," and from *analuein*, which means "to undo." In practical terms, it means "to break apart" or "to separate into its fundamental constituents." Analysis should be compared with the word synthesis. The word *synthesis* comes from the Latin word *suntithenai*, which means "to put together." In practical terms, it means "to combine separate elements to form a whole."

Because of the complexity of most hydrologic engineering design problems, the fundamental elements of the hydrologic sciences cannot be used directly. Instead, it is necessary to take measurements of the response of a hydrologic process and analyze the measurements in an attempt to understand how the process functions. Quite frequently, a model is formulated on the basis of the physical concepts that underlie the process, and the fitting of the model with the measurements provides the basis for understanding how the physical process varies as the input to the process varies. After the measurements have been analyzed (taken apart) to fit the model, the model can be used to synthesize (put together) design rules. That is, the analysis leads to a set of systematic rules that explain how the underlying hydrologic process will function in the future. We recognize that the act of synthesizing is not a total reproduction of the original process. It is a simplification. As with any simplification, it will not provide a totally precise representation of the physical process under all conditions. But in general, it should provide reasonable solutions, especially when many designs based on the same design rules are considered.

It should be emphasized that almost every hydrologic design (or synthesis) was preceded by a hydrologic analysis. Most often, one hydrologic analysis is used as the basis for many, many hydrologic designs. But the important point is that the designer must understand the basis for the analysis that underlies any design method; otherwise, the designer may not apply the design procedure in a way that is compatible with the underlying analysis. This is not to say that a design method cannot be applied without knowing the underlying analysis, only that it is best when the design engineer fully understands the analysis that led to development of the design rules. Anyone can substitute the values of input variables into a design method. But when a design is used under circumstances for which it was not intended to be used, inaccurate designs can be the result. Without further consideration, the engineer uses these estimates as the basis of the design.

1.4.1 Water Budget Analysis and Synthesis

A simplified example may help illustrate the concepts of analysis and synthesis. Let's assume that an engineer has the task of designing a reservoir, and the design requires estimates of the water loss by evaporation from the reservoir. While the design period will be from June 1 to July 31, the engineer is assigned the project just before October 1, with a completion date of April 15 of the following year.

Recognizing his lack of experience in making hydrologic evaluations, the engineer correctly decides to hire a hydrologist to perform an analysis to provide a means of making estimates of evaporation. Recognizing that temperature is an important determinant in the evaporation process, the hydrologist decides to develop a design procedure based on a model relating evaporation to temperature. Since there are no meteorological data collection stations in the region of the design, the hydrologist decides to collect data of the monthly evaporation from a nearby lake and compute the mean monthly temperature. The following data are the result of the data collection effort:

Month	***T* (°F)**	***E* (in.)**
October	70	4.3
November	55	3.3
December	51	3.2
January	50	2.9
February	53	3.1
March	60	3.6

An examination of the literature suggests that evaporation can be related to temperature using a power model $E = b_0 T^{b1}$ with the values of b_0 and b_1 computed using regression analysis. The analysis of the data above led to the model $E = 0.043687T^{1.0792}$ with a correlation coefficient of 0.98, which suggests that the model should be accurate. To summarize, the analysis problem involved (1) deciding on the variables to use, (2) deciding on the form of the model, (3) collecting the matrix of E and T data shown above, and (4) fitting the model to the data and evaluating the expected accuracy of the design model. The hydrologist provides the engineer with the foregoing model.

Given the results of the analysis above, the engineer must now "put together" a design. The engineer knows that the mean temperatures for June and July would be about 85°F and 90°F, respectively. Using these temperatures as input to the design model above, evaporation estimates of 5.3 and 5.6 in., respectively, are obtained. Without further consideration, the engineer uses these estimates as the basis of the design. The high correlation of 0.98 provides the engineer with a false sense of comfort about the accuracy of estimates.

The problem with this description is that the engineer used the results of the analysis (the model) without understanding the analysis. If the hydrologist had known the engineer's objective, the hydrologist would have told the engineer that the model was based on data for the period from October to March, or if the engineer had inquired about the basis for the analysis, the engineer could have made an independent assessment of the results. For example, for the design location the engineer could have compared the design evaporation estimates of 10.9 in. with the mean May–October lake evaporation of 50 in. reported in a climatic atlas. The estimate of 11 in. would then have been rejected as being unreasonably low.

Although this is a simplified example, it is not uncommon for a hydrologic model to be used without the user taking the time to determine the analysis that underlies the model. In cases where the user is fortunate enough to be applying the model within the proper bounds of the analysis, the accuracy of the design is probably within the limits established by the analysis; however, all too often inaccurate designs result because the assumptions used in the analysis are not valid for the particular design. The moral of the story is that those involved in the analysis phase should clearly define the limits of the model, and those involved in synthesis or design should make sure that the design does not require using the model outside the bounds established by the analysis.

1.4.2 A Conceptual Representation

Because of the importance of the concepts of analysis and synthesis, it will be worthwhile to place the problem in a conceptual framework. We will conceptualize the hydrologic system to consist of three parts: the input, the output, and the transfer function. This conceptual framework is shown schematically in Figure 1–3. In the analysis phase, the input and output are known and the analyst must find a rational model of the transfer function. When the analysis phase is completed, either the model of the transfer function or design tools developed from the model are ready to be used in the synthesis phase. In the synthesis or design phase, the design input and the model of the transfer function are known, and the predicted

FIGURE 1–3 Conceptual representation of the systems process.

system output must be computed; the true system output is unknown. The designer predicts the response of the system using the model and bases the engineering design solution of the predicted or synthesized response.

The reservoir design problem can be used to illustrate this conceptual framework of hydrologic analysis and design. In this simplified problem, the evaporation is needed for design; thus the evaporation serves as the output variable. Temperature serves as the input. In the analysis phase, the model for predicting evaporation is evaluated; therefore, the model represents all of the hydrologic processes involved in converting temperature (for example, heat energy) to evaporation. Obviously, temperature is only a single measurement of the processes that effect evaporation, but it is a surrogate variable for these processes in the conceptual representation of the system. In the design phase, the designer uses other temperature conditions as input to the model to predict the response (for example, the output) of the system. It is this synthesis of the system output that is used for the design. In summary, in the analysis phase, the temperature (input) and evaporation (output) were known, while in the synthesis phase, the temperature (input) and the model (transfer function) were known. Examples of the analysis/synthesis representation that will be discussed in other chapters are given in Table 1–1.

1.5 THE HYDROLOGIC BUDGET

The systems concept of Figure 1–3 can be applied to the elements of the hydrologic cycle, which can be viewed as inputs, outputs, and storages. Rainfall can be viewed as an input to the surface of Earth. The surface can be viewed as a series of storage elements, such as storage on the surface of vegetation and depression storage. Runoff from the surface can be viewed as an output from surface storage elements. This would be a systems representation of the physical processes controlling surface runoff.

If river channel processes are the important elements of the hydrologic design, then the surface runoff can be viewed as the input, the channel itself as the storage element, and the runoff out of the channel (into another channel, a lake, or an ocean) as the output from the system. Hydrologic analysts and designers make use of this systems representation of the elements of the hydrologic cycle to develop design methods to solve engineering problems.

The conceptual representation of hydrologic systems can be stated in mathematical terms. Letting I, O, S, and t denote the input, output, storage, and time, respectively, the following equation is known as the linear storage equation:

$$I - O = \frac{dS}{dt} \tag{1–1}$$

The derivative on the right-hand side of Equation 1–1 can be approximated by the numerical equivalent $\Delta S/\Delta t$, when one wishes to examine the change in storage between two times, say t_2 and t_1. In this case, Equation 1–1 becomes

$$I - O = \frac{\Delta S}{\Delta t} = \frac{S_2 - S_1}{t_2 - t_1} \tag{1–2}$$

in which S_2 and S_1 are the storages at times t_2 and t_1, respectively.

TABLE 1–1 Examples of Hydrologic Analysis and Synthesis

			Analysis		Synthesis	
Input	Model or Transfer Function	Output	Known	Unknown	Known	Unknown
1. Runoff coefficient (C) Rainfall intensity (i) Drainage area (A)	Rational formula $Q_p = CiA$ (Eq. 7–20)	Peak discharge (Q_p)	i, A, Q_p	C	C, i, A	Q_p
2. Peak inflow rate (Q_i) Allowable outflow (Q_o) Runoff Volume (V_r)	Figure 8–17	Volume of storage (V_s)	Q_i, Q_o, V_r, V_s	Figure 8–17	Q_i, Q_o, V_r	V_s
3. Upstream hydrograph (I)	Muskingum equation $O_2 = C_0I_2 + C_1I_1 + C_2O_1$ (Eq. 10–53)	Downstream hydrograph (O_2)	I, O_2	C_0, C_1, C_2	I, C_0, C_1, C_2	O_2
4. Erosivity index (R) Soil erodibility factor (K) Topographic factor (T) Cover factor (C) Support factor (P)	Universal soil loss equation $E = RKTCP$ (Eq. 15–14)	Soil loss (E)	E, R, K, T	C, P	R, K, T, C, P	E
5. Length (HL) Slope (Y) Storage (S)	*SCS* lag equation $L = \frac{HL^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$ (Eq. 3–56)	Watershed time lag (L)	L, HL, Y, S	Coefficients of Eq. 3–56	HL, Y, S	L
6. Storage (S) Rainfall (P)	$Q = \frac{(P-0.2S)^2}{P+0.8S}$ (Eq. 7–42)	Runoff Volume (Q)	Q, P	S	P, S	Q

Equation 1–1 can be illustrated using the flow in a river as the input and output. Assume that the inflow and outflow rates to a river reach of 1500 ft in length are 40 ft^3/sec and 30 ft^3/sec, respectively. Therefore, the rate of change in storage equals 10 ft^3/sec or 6000 ft^3 during a 10 min period. Since the inflow is greater than the outflow, the water surface elevation will rise. Assuming an average width of 16 ft, the increased storage would cause the water surface elevation to rise by 6000 ft^3/[16 ft (1500 ft)] = 0.25 ft over the 10 min period.

The storage equation of Equation 1–1 can be used for other types of hydrologic problems. Estimates of evaporation losses from a lake could be made by measuring: all inputs, such as rainfall (I_1), inflow from streams (I_2), and ground-water inflow (I_3); all outputs, such as streamflow out of the lake (O_1), ground-water flow out of the lake (O_2), and evaporation from the lake (O_3); and the change in storage between two time periods, which could be evaluated using the lake levels measured at the beginning and end of the time period. In this case, both the input and the output involve multiple measurements, that is, they are vector quantities with the elements of each vector I_i and O_j representing the different components of the inflow and outflow from the system. The unknown is one of the elements of the outflow vector. Mathematically, the water balance is

$$(I_1 + I_2 + I_3) - (O_1 + O_2 + O_3) = \frac{dS}{dt} \tag{1-3}$$

Estimating evaporation losses (O_3) would require measurements of each of the inflows, the other outflows, and lake levels; obviously, any errors in the measurements of the elements of Equation 1–3 would effect the accuracy of the estimated evaporation. Also, if there are any inflows other than I_1, I_2, and I_3 or any outflows other than O_1 and O_2, the estimated evaporation will be in error by such amounts.

In summary, the hydrologic budget is a convenient way of modeling the elements of the hydrologic cycle. It will be used frequently in describing the problems of analysis and design.

1.6 INTRODUCTION TO PROFESSIONAL ETHICS

The chapters of this book detail various methods of hydrologic analysis and design. This may imply that the heart of hydrologic work is the number crunching. While the hydrologist must certainly understand the physical processes and know the design procedures, he or she must also recognize that designs are necessary because society has needs and problems. Very often these needs or problems arise because of value issues. An adequate water supply is important for both the public health and the happiness of citizens. But a dam and reservoir may represent a hazard to public safety. The hydrologist will be involved in the technical aspects of solving the problem, but the hydrologist has social responsibilities related to the value issues. These value issues should be just as important to the hydrologist as the technical details are. Sound hydrologic practice is not limited to providing correct evaluations of the design elements. Hydrologists must be able to recognize value issues, be willing and able to consider the value issues along with the technical issues, and know how to incorporate these value issues into decision making. These value-based responsibilities are just as important as the design responsibilities.