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Hydrology: Introduction to Hydrology and Precipitation

PDH Credits:
4 PDH

Course No.:
HR1101

Publication Source:

US DOT - FHWA

"Hydraulic Design Series No. 2, 2nd Edition - Highway Hydrology"
Pub. # FHWA - NHI-02-001

Release Date:
Oct. 2002

1265 San Juan Dr. - Merritt Island, FL 32952
Phone: 321-501-5601

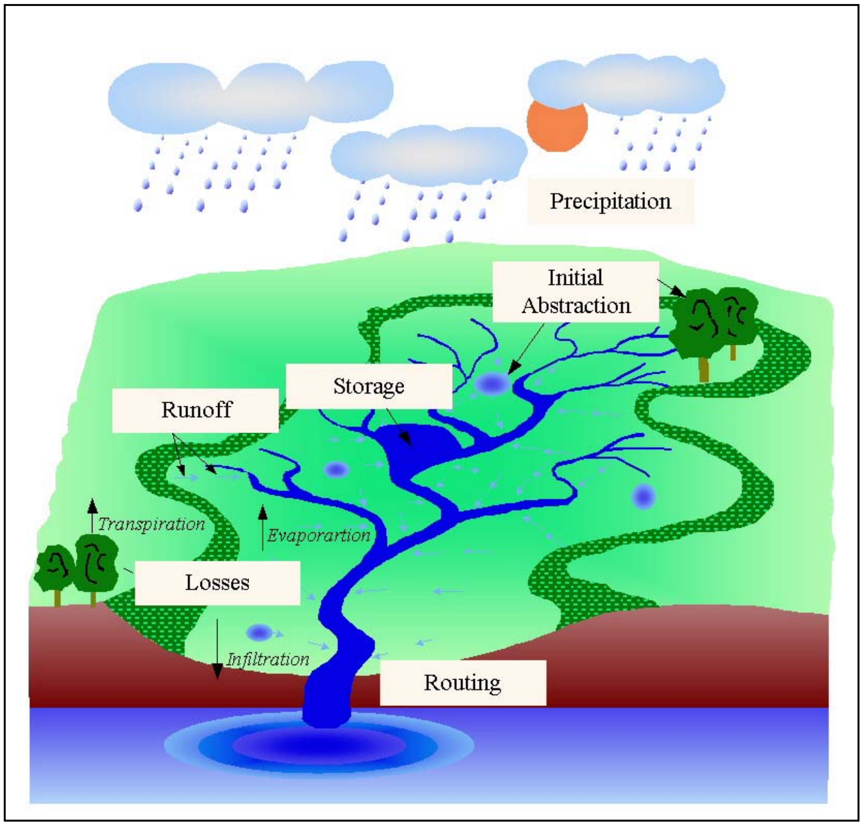
Publication No. FHWA-NHI-02-001
October 2002

U.S. Department of Transportation

Federal Highway Administration

Hydraulic Design Series No. 2, Second Edition

Highway Hydrology



National Highway Institute

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CHAPTER 1

INTRODUCTION

Hydrology is often defined as the science that addresses the physical properties, occurrence, and movement of water in the atmosphere, on the surface of, and in the outer crust of the earth. This is an all-inclusive and somewhat controversial definition as there are individual bodies of science dedicated to the study of various elements contained within this definition. Meteorology, oceanography, and geohydrology, among others, are typical. For the highway designer, the primary focus of hydrology is the water that moves on the earth's surface and in particular that part that ultimately crosses transportation arterials (i.e., highway stream crossings). A secondary interest is to provide interior drainage for roadways, median areas, and interchanges.

Hydrologists have been studying the flow or runoff of water over land for many decades, and some rather sophisticated theories have been proposed to describe the process. Unfortunately, most of these attempts have been only partially successful, not only because of the complexity of the process and the many interactive factors involved, but also because of the stochastic nature of rainfall, snowmelt, and other sources of water. Hydrologists have defined most of the factors and parameters that influence surface runoff. However, for many of these surface runoff factors, complete functional descriptions of their individual effects exist only in empirical form. Their qualitative analysis requires extensive field data, empirically determined coefficients, and sound judgment and experience.

By application of the principles and methods of modern hydrology, it is possible to obtain solutions that are functionally acceptable and form the basis for the design of highway drainage structures. It is the purpose of this manual to present some of these principles and techniques and to explain their uses by illustrative examples. First, however, it is desirable to discuss some of the basic hydrologic concepts that will be utilized throughout the manual and to discuss hydrologic analysis as it relates to the highway stream-crossing problem.

1.1 HYDROLOGIC CYCLE

Water, which is found everywhere on the earth, is one of the most basic and commonly occurring substances. Water is the only substance on earth that exists naturally in the three basic forms of matter (i.e., liquid, solid, and gas). The quantity of water varies from place to place and from time to time. Although at any given moment the vast majority of the earth's water is found in the world's oceans, there is a constant interchange of water from the oceans to the atmosphere to the land and back to the ocean. This interchange is called the hydrologic cycle.

The hydrologic cycle, illustrated in Figure 1.1, is a description of the transformation of water from one phase to another and its motion from one location to another. In this context, it represents the complete descriptive cycle of water on and near the surface of the earth.

Beginning with atmospheric moisture, the hydrologic cycle can be described as follows: When warm, moist air is lifted to the level at which condensation occurs, precipitation in the form of rain, hail, sleet, or snow forms and then falls on a watershed. Some of the water evaporates as it falls and the rest either reaches the ground or is intercepted by buildings, trees, and other vegetation. The intercepted water evaporates directly back to the atmosphere, thus completing a part of the cycle. The remaining precipitation reaches the ground's surface or onto the water surfaces of rivers, lakes, ponds, and oceans.

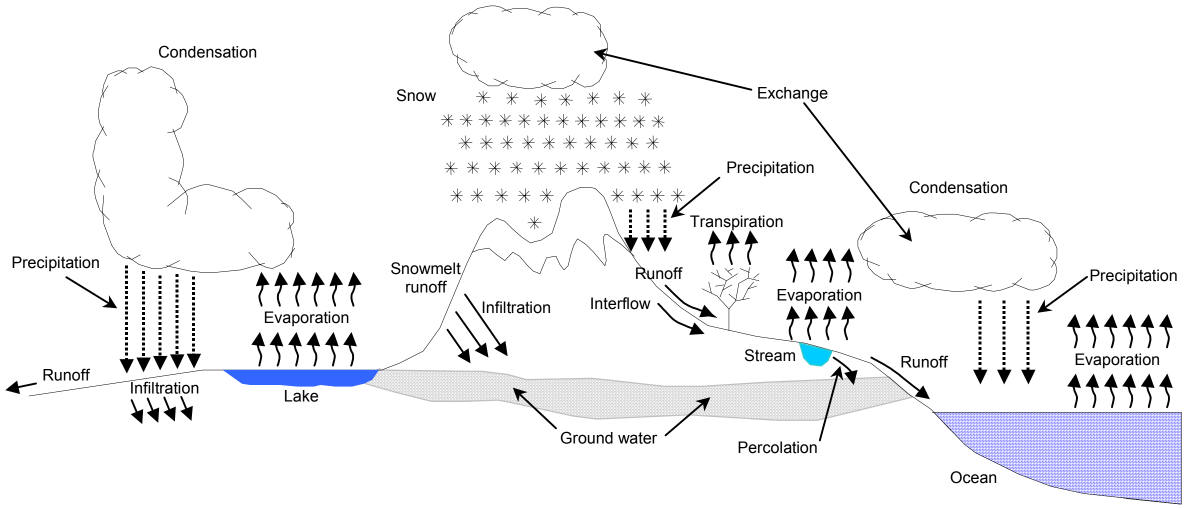


Figure 1.1. The hydrologic cycle

If the precipitation falls as snow or ice, and the surface or air temperature is sufficiently cold, this frozen water will be stored temporarily as snowpack to be released later when the temperature increases and melting occurs. While contained in a snowpack, some of the water escapes through sublimation, the process where frozen water (i.e., ice) changes directly into water vapor and returns to the atmosphere without entering the liquid phase. When the temperature exceeds the melting point, the water from snowmelt becomes available to continue in the hydrologic cycle.

The water that reaches the earth's surface evaporates, infiltrates into the root zone, or flows overland into puddles and depressions in the ground or into swales and streams. The effect of infiltration is to increase the soil moisture. Field capacity is the moisture held by the soil after all gravitational drainage. If the moisture content is less than the field capacity of the soil, water returns to the atmosphere through soil evaporation and by transpiration from plants and trees. If the moisture content becomes greater than the field capacity, the water percolates downward to become ground water.

The part of precipitation that falls into puddles and depressions can evaporate, infiltrate, or, if it fills the depressions, the excess water begins to flow overland until eventually it reaches natural drainageways. Water held within the depressions is called depression storage and is not available for overland flow or surface runoff.

Before flow can occur overland and in the natural and/or manmade drainage systems, the flow path must reach its storage capacity. This form of storage, called detention storage, is temporary since most of this water continues to drain after rainfall ceases. The precipitation that percolates down to ground water is maintained in the hydrologic cycle as seepage into streams and lakes, as capillary movement back into the root zone, or it is pumped from wells and discharged into irrigation systems, sewers, or other drainageways. Water that reaches streams and rivers may be detained in storage reservoirs and lakes or it eventually reaches the oceans. Throughout this path, water is continually evaporated back to the atmosphere, and the hydrologic cycle is repeated.

1.2 HYDROLOGY OF HIGHWAY STREAM CROSSINGS

In highway engineering, the diversity of drainage problems is broad and includes the design of pavements, bridges, culverts, siphons, and other cross drainage structures for channels varying from small streams to large rivers. Stable open channels and stormwater collection, conveyance, and detention systems must be designed for both urban and rural areas. It is often necessary to evaluate the impacts that future land use, proposed flood control and water supply projects, and other planned and projected changes will have on the design of the highway crossing. On the other hand, the designer also has a responsibility to adequately assess flood potentials and environmental impacts that planned highway and stream crossings may have on the watershed.

1.2.1 Elements of the Hydrologic Cycle Pertinent to Stream Crossings

In highway design, the primary concern is with the surface runoff portion of the hydrologic cycle. Depending on local conditions, other elements may be important; however, evaporation and transpiration can generally be discounted. The four most important parts of the hydrologic cycle to the highway designer are: (1) precipitation, (2) infiltration, (3) storage, and (4) surface runoff. Runoff processes are discussed in Chapter 2.

Precipitation is very important to the development of hydrographs and especially in synthetic unit hydrograph methods and some peak discharge formulas where the flood flow is determined in part from excess rainfall or total precipitation minus the sum of the infiltration and storage. As described above, infiltration is that portion of the rainfall that enters the ground surface to become ground water or to be used by plants and trees and transpired back to the atmosphere. Some infiltration may find its way back to the tributary system as interflow moving slowly near the ground surface or as ground-water seepage, but the amount is generally small. Storage is the water held on the surface of the ground in puddles and other irregularities (depression storage) and water stored in more significant quantities often in human-made structures (detention storage). Surface runoff is the water that flows across the surface of the ground into the watershed's tributary system and eventually into the primary watercourse.

The task of the designer is to determine the quantity and associated time distribution of runoff at a given highway stream crossing, taking into account each of the pertinent aspects of the hydrologic cycle. In most cases, it is necessary to make approximations of these factors. In some situations, values can be assigned to storage and infiltration with confidence, while in others, there may be considerable uncertainty, or the importance of one or both of these losses may be discounted in the final analysis. Thorough study of a given situation is necessary to permit assumptions to be made, and often only acquired experience or qualified advice permit solutions to the more complex and unique situations that may arise at a given crossing.

1.2.2 Overview of Hydrology as Applied to Stream Crossings

In many hydrologic analyses, the three basic elements are: (1) measurement, recording, compilation, and publication of data; (2) interpretation and analysis of data; and (3) application to design or other practical problems.

The development of hydrology for a highway stream crossing is no different. Each of these tasks must be performed, at least in part, before an actual hydraulic structure can be designed. How extensively involved the designer becomes with each depends on: (1) importance and cost of the structure or the acceptable risk of failure; (2) amount of data available for the analysis; (3) additional information and data needed; (4) required accuracy; and (5) time and other resource constraints.

These factors normally determine the level of analysis needed and justified for any particular design situation. As practicing designers will confirm, they may be confronted with the problems of insufficient data and limited resources (time, manpower, and money). It is impractical in routine design to use analytical methods that require extensive time and manpower or data not readily available or that are difficult to acquire. The more demanding methods and techniques should be reserved for those special projects where additional data collection and accuracy produce benefits that offset the additional costs involved. Examples of techniques requiring large amounts of time and data include basinwide computer simulation and rainfall-runoff models such as HEC-1 or HEC-HMS, developed by the U.S. Army Corps of Engineers (USACE), and TR-20, developed by the Soil Conservation Service (SCS). (The SCS has been renamed the Natural Resources Conservation Service (NRCS)).

There are, however, a number of simpler but equally sound and proven methods available to analyze the hydrology for some common design problems. These procedures enable peak flows and hydrographs to be determined without an excessive expenditure of time and that use existing data or, in the absence of data, synthesize methods to develop the design parameters. With care, and often with only limited additional data, these same procedures can be used to develop the hydrology for the more complex and/or costly design projects.

The choice of an analytical method is a decision that must be made as each problem arises. For this to be an informed decision, the designer must know what level of analysis is justified, what data are available or must be collected, and what methods of analysis are available together with their relative strengths and weaknesses in terms of cost and accuracy.

Exclusive of the effects a given design may have upstream or downstream in a watershed, hydrologic analysis at a highway stream crossing requires the determination of either peak flow or the flood hydrograph. Peak discharge (sometimes called the instantaneous maximum discharge) is critical because most highway stream crossings are traditionally designed to pass a given quantity of water with an acceptable level of risk. This capacity is usually specified in terms of the peak rate of flow during passage of a flood, called peak discharge or peak flow. Associated with this flow is a flood severity that is defined based on a predictable frequency of occurrence (i.e., a 10-year flood, a 50-year flood, etc.). Table 1.1 provides examples of some typical design frequencies for hydraulic structures associated with different roadway classifications, as identified in drainage guidance developed by the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 1999).

Generally, the task of the highway designer is to determine the peak flows for a range of flood frequencies at a site in a drainage basin. Culverts, bridges, or other structures are then sized to convey the design peak discharge within other constraints imposed on the design. If possible, the peak discharge that almost causes highway overtopping is estimated, and this discharge is then used to evaluate the risk associated with the crossing.

Hydrograph development is important where a detailed description of the time variation of runoff rates and volumes is required. Similarly, urbanization, storage, and other changes in a watershed affect flood flows in many ways. Travel time, time of concentration, runoff duration, peak flow, and the volume of runoff may be changed by very significant amounts. The flood hydrograph is the primary way to evaluate and assess these changes. Additionally, when flows are combined and routed to another point along a stream, hydrographs are essential.

Table 1.1. Design Storm Selection Guidelines (AASHTO, 1999)

Roadway Classification	Exceedence Probability	Return Period
Rural Principal Arterial System	2%	50-year
Rural Minor Arterial System	4% - 2%	25-50-year
Rural Collector System, Major	4%	25-year
Rural Collector System, Minor	10%	10-year
Rural Local Road System	20% - 10%	5-10-year
Urban Principal Arterial System	4% - 2%	25-50-year
Urban Minor Arterial Street System	4%	25-year
Urban Collector Street System	10%	10-year
Urban Local Street System	20% - 10%	5-10-year

Note: Federal regulations require interstate highways to be provided with protection from the 2 percent flood event. AASHTO recommends that facilities such as underpasses, depressed roadways, etc., where no overflow relief is available should also be designed for the 2 percent flood event (AASHTO, 1999).

Neither peak flow nor hydrographs present any real computational difficulties provided data are available for their determination. A problem faced by the highway designer is that insufficient flow data, or often no data, exist at the site where a stream crossing is to be designed. Although data describing the topography and the physical characteristics of the basin are readily attainable, rarely is there sufficient time to collect the flow data necessary to evaluate peak flows and hydrographs. In this case, the designer must resort to synthetic methods to develop design parameters. These methods require considerably more judgment and understanding in order to evaluate their application and reliability.

Finally, the designer must be constantly alert to changing or the potential for changing conditions in a watershed. This is especially important when reviewing reported stream flow data for a watershed that has undergone urban development, and channelization, diversions, and other drainage improvements. Similarly, the construction of reservoirs, flow regulation measures, stock ponds, and other storage facilities in the basin may be reflected in stream flow data. Other factors such as change in gauge datum, moving of a gauge, or mixed floods (floods caused by rainfall and snowmelt or rainfall and hurricanes) must be carefully analyzed to avoid misinterpretation and/or incorrect conclusions.

1.2.3 Channelization

Channelization is the process of modifying the hydraulic conveyance of a natural watershed. This is usually done to improve the hydraulic efficiency of the main channel and tributaries and thereby alleviate localized flooding problems. On the other hand, these channelized areas usually have an increase in the peak discharge and a decrease in the time to peak of the runoff hydrograph.

Various urban studies such as that by Liscum and Massey (1980) have shown that the impacts of channelization on flood characteristics may be as significant as the encroachment of impervious cover. Therefore, the designer must be able to evaluate the effects of channelization work done by others on highway design as well as any channel modifications made in conjunction with highway construction.

1.2.4 Detention Storage

Temporary in-channel or detention storage usually reduces peak discharges. Unfortunately, there is no simple way to determine the effect of detention storage at a specified urban site. The reservoir- and channel-routing techniques discussed in Chapter 7 can be used to make assessments of these quantities.

1.2.5 Diversions and Dam Construction

The highway designer needs to be aware of the construction or planned construction of diversions or dams on the watershed because these works will significantly affect the magnitude and character of the runoff reaching the highway crossing. The designer should make a point to become informed of proposed projects being studied by the various water resources agencies active in their part of the country. Local agencies such as power utilities, irrigation boards, and water supply companies should be canvassed whenever a major highway drainage structure is designed. The methods of channel and reservoir routing can be used to assess the effects that such projects will have on highway drainage. Recently, the practice of decommissioning dams has increased. Effects on drainage of highways downstream need to be considered.

1.2.6 Natural Disasters

Highways are considered permanent structures. Although it is rarely economically feasible to design a highway drainage structure to convey extremely rare discharges unimpeded, the occurrence of such events should not be ignored. Many highway departments have adopted policies that require drainage structures to be designed for a specified recurrence interval, but checked for a higher recurrence interval (often the 100-year discharge, the overtopping flood or the flood of record). Chapter 4 states that there is a 40 percent chance that, during a 50-year period, a drainage structure will be subjected to a discharge equal to or greater than the 100-year discharge. The longer the design life of a structure, the more likely it will be subjected to a discharge much greater than the design discharge. This risk can be quantified based upon the laws of probability, and this is discussed in more detail in Chapter 4 (risk assessment).

Checking for the effects of a rare event is one method of focusing the designer's attention upon this aspect of design. However, factors other than discharge must be evaluated. These include the occurrence of earthquakes, forest fires, dam breaks, and other unlikely but possible events. The designer needs to assess the vulnerability of the particular site with respect to the effects of these occurrences and consider secondary outlets for the flows. It is very difficult to assign a recurrence interval to such natural disasters, but their impacts need to be assessed.

The effects of forest fires upon the rainfall-runoff response of a watershed can be estimated based upon previous experience. The U.S. Forest Service can be contacted to provide guidance in this area. The effects of dam breaks have been studied by the National Weather Service (NWS) and documentation by the NWS is available for consultation and guidance.

After a natural disaster strikes, detailed studies of the effects may be made and reports generated that can serve as guidance to the designer. The NWS, the U.S. Geological Survey (USGS), and the Corps of Engineers are the primary sources of such reports. The primary responsibility for disaster recovery within the Federal Government rests with the Federal Emergency Management Agency (FEMA).

1.3 GENERAL DATA REQUIREMENTS

Regardless of the method selected for the analysis of a particular hydrologic problem, there is a need for data or analysis methods that are based on statistical manipulation of data. These needs take a variety of forms and may include data on precipitation and stream flow, information about the watershed, and the project to be designed. The type, amount, and availability of the data will be determined in part by the method selected for the design.

1.4 SOLUTION METHODS

Available analytical methods can be grouped into the two broad categories of deterministic and statistical methods. Deterministic methods strive to model the physical aspects of the rainfall-runoff process while statistical methods utilize measured data to fit functions that represent the process. Deterministic methods can either be conceptual, where each element of the runoff process is accounted for in some manner, or they may be empirical, where the relationship between rainfall and runoff is quantified based on measured data and experience. For example, unit hydrograph methods are deterministic. Statistical methods apply the techniques and procedures of modern statistical analysis to actual or synthetic data and fit the needed design parameters directly. Flood frequency analysis and peak-discharge regression equations are examples of the statistical approach.

1.4.1 Deterministic Methods

Deterministic methods often require a large amount of judgment and experience to be used effectively. These methods depend heavily upon the approach used, and it is not uncommon for two different designers to arrive at different estimates of runoff for the same watershed. The accuracy of deterministic methods is also difficult to quantify. However, deterministic methods are usually based on fundamental concepts, and there is often an intuitive "rightness" about them that has led to their widespread acceptance in highway and other design practice. An experienced designer, familiar with a particular deterministic method, can arrive at reasonable solutions in a relatively short period of time. Unit hydrograph methods such as the SCS TR-20 program and the Corps of Engineers HEC-1 program are deterministic methods. Hydrologic channel routing methods such as the Muskingum method are deterministic.

1.4.2 Statistical Methods

Statistical methods, in general, do not require as much subjective judgment and experience to apply as deterministic methods. They are usually well-documented mathematical procedures that are applied to measured or observed data. The predictions of one designer should be very nearly the same as those of another who applies the same procedures with the same data. The accuracy of statistical methods can also be measured quantitatively. However, statistical methods may not be well understood and, as a result, answers may be misinterpreted. To provide clear guidance, this manual presents the commonly accepted statistical methods for peak flow determination in a logical format that is compatible with the practical needs of highway drainage design.

1.5 ANALYSIS VERSUS SYNTHESIS

Like most of the basic sciences, hydrology requires both analysis and synthesis to use 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." The meanings of the words analysis and synthesis given here may differ from common usage. Specifically, practicing engineers often use analysis as a synonym for design. This difference needs to be recognized and understood.

Because of the complexity of many hydrologic engineering 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 hydrologic 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 (i.e., taken apart) to fit the model, the model can be used to synthesize (i.e., put together) design rules. That is, the analysis leads to a set of systematic rules that explain how the underlying hydrologic processes will function in the future. The act of synthesizing is not, of course, 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 basis, 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, inaccurate designs could be the result.

Hydrologic models are commonly 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, inaccurate designs can result because the assumptions used in the analysis are not valid for the particular design. 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.

1.5.1 A Conceptual Representation of Analysis and Synthesis

Because of the importance of the concepts of analysis and synthesis, it may be worthwhile to place the design problem in a conceptual hydrologic system of three parts: the input, the output, and the transfer function. This conceptual framework is shown schematically in Figure 1.2. 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 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 on the predicted or synthesized response.

1.5.2 Examples of Analysis and Synthesis in Hydrologic Design

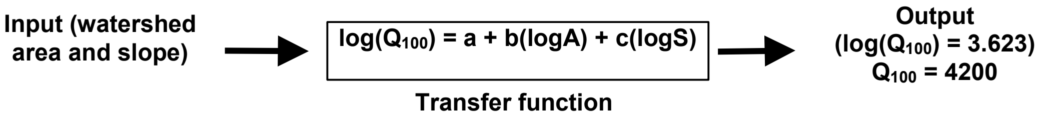
Two hydrologic design methods available to the highway engineer are peak-discharge regression equations and unit hydrograph models. These can be used to illustrate factors that must be considered in analysis and synthesis.

Peak-discharge regression equations are commonly used for the design of a variety of highway facilities, such as bridges, culverts, and roadway inlets. In the analysis phase, the input consists of values of watershed characteristics at gauged stations in a homogeneous region. The output is the peak discharge values for a selected return period from frequency analyses at gauged locations. The transfer function, or model, is the power model with unknown regression coefficients. Least-squares regression analyses usually use the watershed characteristics and peak discharge magnitudes from the known watersheds to fit the unknown coefficients. Important assumptions are made in this phase of modeling. Although these assumptions may limit the use of the equations, they are necessary. Specifically, only gauged data from unregulated streams are used. Additionally, stream records used in the frequency analyses should not include watersheds that have undergone extensive watershed change, such as urbanization or deforestation, unless this is specifically accounted for in the flood frequency analyses. Each of the watershed characteristics applies to certain ranges; for example, the drainage areas included in the analyses may range from 50 to 200 square kilometers (20 to 80 square miles). These limits are important to know so that the model is not used without caution beyond the ranges of the inputs used to fit the equation. Failure to understand these factors can lead to an inappropriate use of the fitted model.

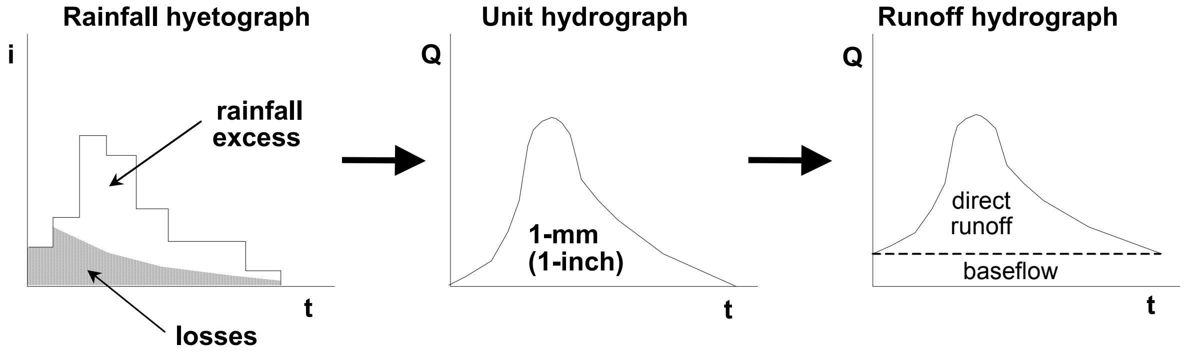
It is important to know the accuracy that can be expected of a model, which might be indicated by a standard error of estimate or correlation coefficient of the fitted model. This is important if the engineer wants to compare alternative models when selecting a design method and when the engineer is considering the accuracy of the design. This is also important if the designer wants to compare alternative models when selecting a design method and when considering the accuracy of a design.

In the synthesis phase, the fitted model and values of watershed characteristics at an ungauged location are available; these represent the transfer function and input, respectively. The output is the computed discharge estimate. There is no direct way to assess the accuracy of the design estimate, so the accuracy statistics of the fitted equation are used as estimates of the accuracy of the computed value.

(a) Conceptual representation of a system



(b) Example: peak discharge regression equation



(c) Example: unit hydrograph model

Figure 1.2. Concept and examples of the systems analysis and synthesis process

Unit hydrograph models, which are introduced in Chapter 6, can be used for design work where either the watershed is not homogeneous or storage is a significant factor. To develop a unit hydrograph, which is the transfer function, both a measured rainfall hyetograph and the storm hydrograph measured for the same storm event are needed. The hyetograph is the input function and the hydrograph is the output function. When possible, hyetographs and hydrographs for several storm events should be available to fit unit hydrographs. Then the individual unit hydrographs can be averaged to obtain a more representative unit hydrograph.

An engineer who uses the unit hydrograph for design work should know factors such as the size and character of the watersheds from which it was developed. A unit hydrograph based on data from a coastal area may lead to underdesign if it is used on a mountainous watershed. If the fitted unit hydrograph does not provide an accurate reproduction of the outflow hydrographs used in its development, it will not be reliable and should be used with caution.

In the synthesis phase, the unit hydrograph, as the transfer function, is used with a design storm, which is the input function. The design hydrograph obtained by convolving the design storm and unit hydrograph is the output function. The accuracy of the design hydrograph will depend on the accuracy of the unit hydrograph and its appropriateness for the watershed for which the design is being made.

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CHAPTER 2

RAINFALL/RUNOFF PROCESSES

From the discussion of the hydrologic cycle in Chapter 1, the runoff process can be defined as that collection of interrelated natural processes by which water, as precipitation, enters a watershed and then leaves as runoff. In other words, surface runoff is the portion of the total precipitation that has not been removed by processes in the hydrologic cycle. The amount of precipitation that runs off from the watershed is called the "rainfall excess", and "hydrologic abstractions" is the commonly used term that groups all of the processes that extract water from the original precipitation. It follows then that the volume of surface runoff is equal to the volume of rainfall excess, or, in the case of the typical highway problem, the runoff is the original precipitation less infiltration and storage.

The primary purpose of this chapter is to describe more fully the runoff process. An understanding of the process is necessary to properly apply hydrologic design methods. Pertinent aspects of precipitation are identified and each of the hydrologic abstractions is discussed in some detail. The important characteristics of runoff are then defined together with how they are influenced by different features of the drainage basin. The chapter includes a qualitative discussion of the runoff process, beginning with precipitation and illustrating how this input is modified by each of the hydrologic abstractions. Because the time characteristics of runoff are important in design, a discussion of runoff travel time parameters is included.

2.1 PRECIPITATION

Precipitation is the water that falls from the atmosphere in either liquid or solid form. It results from the condensation of moisture in the atmosphere due to the cooling of a parcel of air. The most common cause of cooling is dynamic or adiabatic lifting of the air. Adiabatic lifting means that a given parcel of air is caused to rise with resultant cooling and possible condensation into very small cloud droplets. If these droplets coalesce and become of sufficient size to overcome the air resistance, precipitation in some form results.

2.1.1 Forms of Precipitation

Precipitation occurs in various forms. Rain is precipitation that is in the liquid state when it reaches the earth. Snow is frozen water in a crystalline state, while hail is frozen water in a 'massive' state. Sleet is melted snow that is an intermixture of rain and snow. Of course, precipitation that falls to earth in the frozen state cannot become part of the runoff process until melting occurs. Much of the precipitation that falls in mountainous areas and in the northerly latitudes falls in the frozen form and is stored as snowpack or ice until warmer temperatures prevail.

2.1.2 Types of Precipitation (by Origin)

Precipitation can be classified by the origin of the lifting motion that causes the precipitation. Each type is characterized by different spatial and temporal rainfall regimens. The three major types of storms are classified as convective storms, orographic storms, and cyclonic storms. A fourth type of storm is often added, the hurricane or tropical cyclone, although it is a special case of the cyclonic storm.

2.1.2.1 Convective Storms

Precipitation from convective storms results as warm moist air rises from lower elevations into cooler overlying air as shown in Figure 2.1. The characteristic form of convective precipitation is the summer thunderstorm. The surface of the earth is warmed considerably by mid- to late afternoon of a summer day, the surface imparting its heat to the adjacent air. The warmed air begins rising through the overlying air, and if proper moisture content conditions are met (condensation level), large quantities of moisture will be condensed from the rapidly rising, rapidly cooling air. The rapid condensation may often result in huge quantities of rain from a single thunderstorm spawned by convective action, and very large rainfall rates and depths are quite common beneath slowly moving thunderstorms.

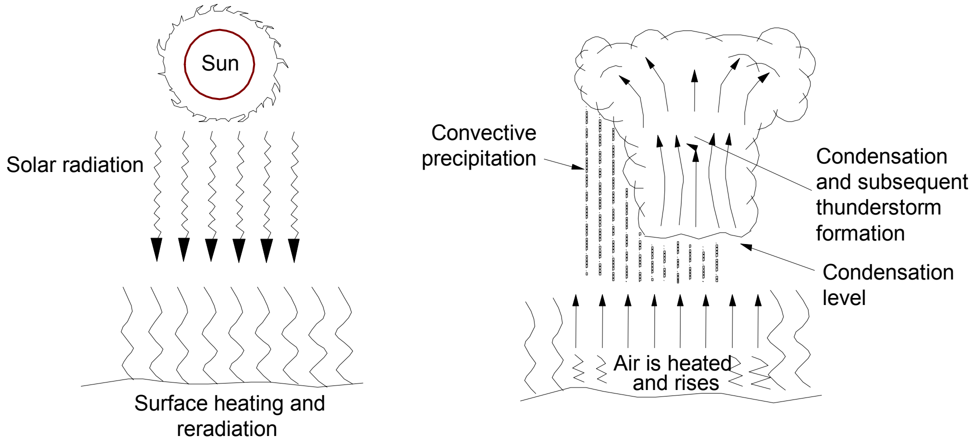


Figure 2.1. Convective storm

2.1.2.2 Orographic Storms

Orographic precipitation results as air is forced to rise over a fixed-position geographic feature such as a range of mountains (see Figure 2.2). The characteristic precipitation patterns of the Pacific coastal states are the result of significant orographic influences. Mountain slopes that face the wind (windward) are much wetter than the opposite (leeward) slopes. In the Cascade Range in Washington and Oregon, the west-facing slopes may receive upwards of 2500 mm (100 in) of precipitation annually, while the east-facing slopes, only a short distance away over the crest of the mountains, receive on the order of 500 mm (20 in) of precipitation annually.

2.1.2.3 Cyclonic Storms

Cyclonic precipitation is caused by the rising or lifting of air as it converges on an area of low pressure. Air moves from areas of higher pressure toward areas of lower pressure. In the middle latitudes, cyclonic storms generally move from west to east and have both cold and warm air associated with them. These mid-latitude cyclones are sometimes called extra-tropical cyclones or continental storms.

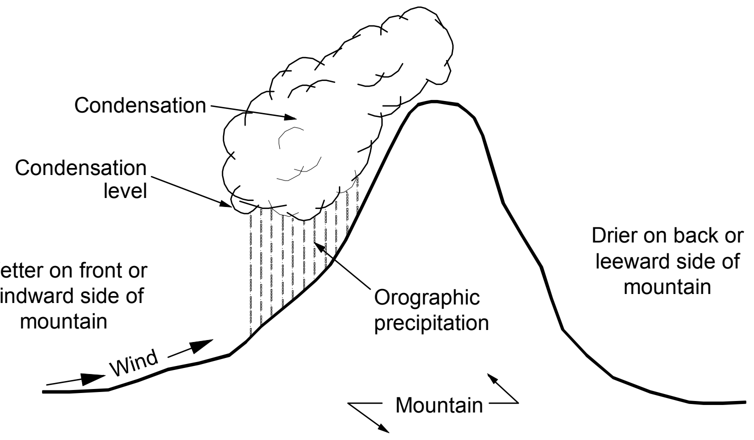


Figure 2.2. Orographic storm

Continental storms occur at the boundaries of air of significantly different temperatures. A disturbance in the boundary between the two air parcels can grow, appearing as a wave as it travels from west to east along the boundary. Generally, on a weather map, the cyclonic storm will appear as shown in Figure 2.3, with two boundaries or fronts developed. One has warm air being pushed into an area of cool air, while the other has cool air pushed into an area of warmer air. This type of air movement is called a front; where warm air is the aggressor, it is a warm front, and where cold air is the aggressor, it is a cold front (see Figure 2.4). The precipitation associated with a cold front is usually heavy and covers a relatively small area, whereas the precipitation associated with a warm front is more passive, smaller in quantity, but covers a much larger area. Tornadoes and other violent weather phenomena are associated with cold fronts.

2.1.2.4 Hurricanes and Typhoons

Hurricanes, typhoons, or tropical cyclones develop over tropical oceans that have a surface-water temperature greater than 29°C (84°F). A hurricane has no trailing fronts, as the air is uniformly warm since the ocean surface from which it was spawned is uniformly warm. Hurricanes can drop tremendous amounts of moisture on an area in a relatively short time. Rainfall amounts of 350 to 500 mm (14 to 20 in) in less than 24 hours are common in well-developed hurricanes, where winds are often sustained in excess of 120 km/h (75 mi/h).

2.1.3 Characteristics of Rainfall Events

The characteristics of precipitation that are important to highway drainage are the intensity (rate of rainfall); the duration; the time distribution of rainfall; the storm shape, size, and movement; and the frequency.

Intensity is defined as the time rate of rainfall depth and is commonly given in the units of millimeters per hour (inches per hour). All precipitation is measured as the vertical depth of water (or water equivalent in the case of snow) that would accumulate on a flat level surface if all the precipitation remained where it fell. A variety of rain gauges have been devised to measure precipitation. All first-order weather stations use gauges that provide nearly continuous records of accumulated rainfall with time. These data are typically reported in either tabular form or as cumulative mass rainfall curves (see Figure 2.5).

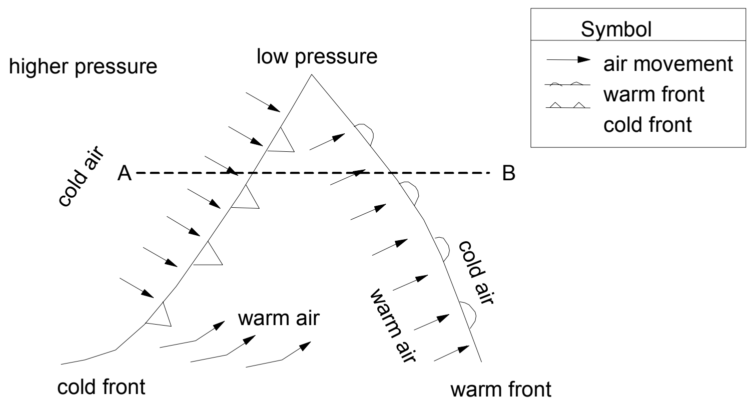


Figure 2.3. Storm as it appears on weather map in the northern hemisphere

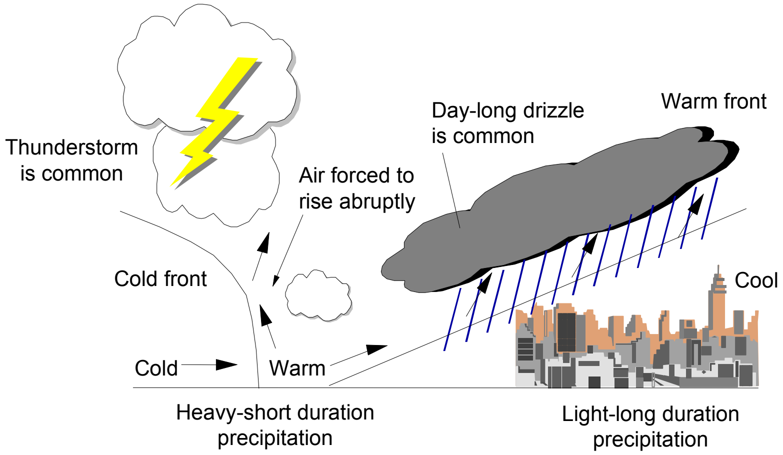


Figure 2.4. Cyclonic storms in mid-latitude; cross-section from A to B of Figure 2.3

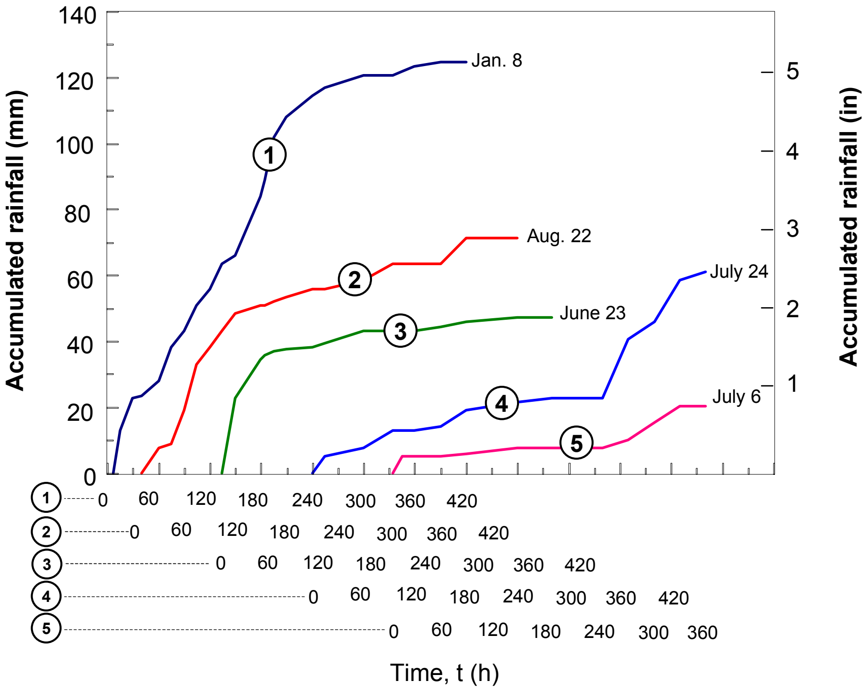


Figure 2.5. Typical mass rainfall curves: Kickapoo Station recording gauge

In any given storm, the instantaneous intensity is the slope of the mass rainfall curve at a particular time. For hydrologic analysis, it is desirable to divide the storm into convenient time increments and to determine the average intensity over each of the selected periods. These results are then plotted as rainfall hyetographs, two examples of which are shown in Figure 2.6 for the Kickapoo Station.

While the above illustrations use a 1-hour time increment to determine the average intensity, any time increment compatible with the time scale of the hydrologic event to be analyzed can be used. Figure 2.6 shows the irregular and complex nature of different storms measured at the same station.

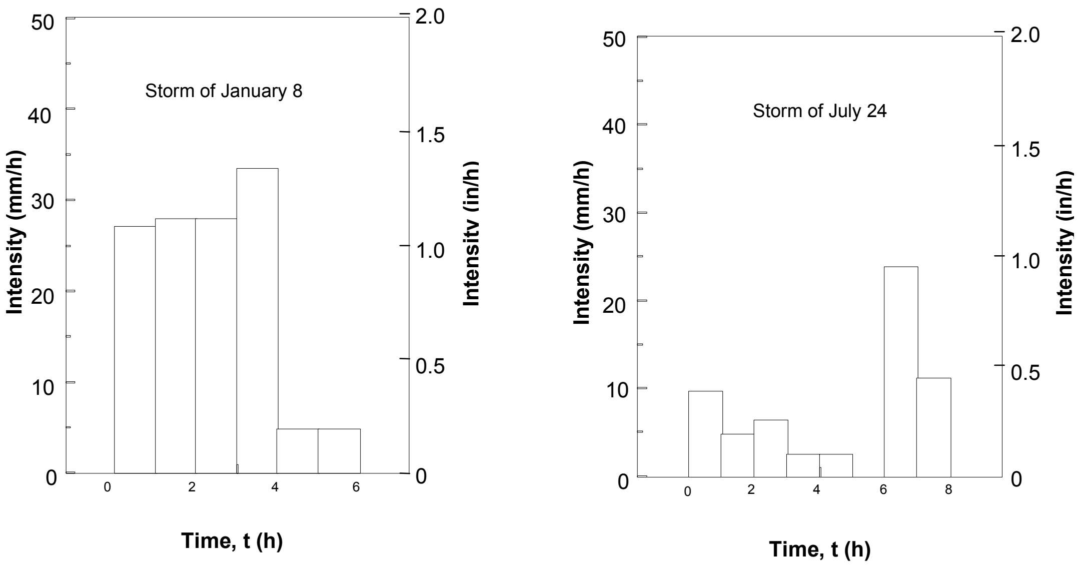


Figure 2.6. Rainfall hyetographs for Kickapoo Station

In spite of this complexity, intensity is the most important of the rainfall characteristics. All other factors being equal, the more intense the rainfall, the larger will be the discharge rate from a given watershed. Intensities can vary from misting conditions where a trace of precipitation may fall to cloudbursts. Figure 2.7 summarizes some of the maximum observed rainfalls in the United States. The events given in Figure 2.7 are depth-duration values at a point and can only be interpreted for average intensities over the reported durations. Still some of these storms were very intense, with average intensities on the order of 150 to 500 mm/h (6 to 20 in/h) for the shorter durations (<1 hour) and from 50 to 250 mm/h (2 to 10 in/h) for the longer durations (>1 hour). Since these are only averages, it is probable that intensities in excess of these values occurred during the various storms.

The storm duration or time of rainfall can be determined from either Figure 2.5 or 2.6. In the case of Figure 2.5, the duration is the time from the beginning of rainfall to the point where the mass curve becomes horizontal, indicating no further accumulation of precipitation. In Figure 2.6, the storm duration is simply the width (time base) of the hyetograph. The most direct effect of storm duration is on the volume of surface runoff, with longer storms producing more runoff than shorter duration storms of the same intensity.

The time distribution of the rainfall is normally given in the form of intensity hyetographs similar to those shown in Figure 2.6. This time variation directly determines the corresponding distribution of the surface runoff. As illustrated in Figure 2.8, high intensity rainfall at the beginning of a storm, such as the January 8 storm in Figure 2.6, will usually result in a rapid rise in the runoff, followed by a long recession of the flow. Conversely, if the more intense rainfall occurs toward the end of the duration, as in the July 24 storm of Figure 2.6, the time to peak will be longer, followed by a rapidly falling recession.

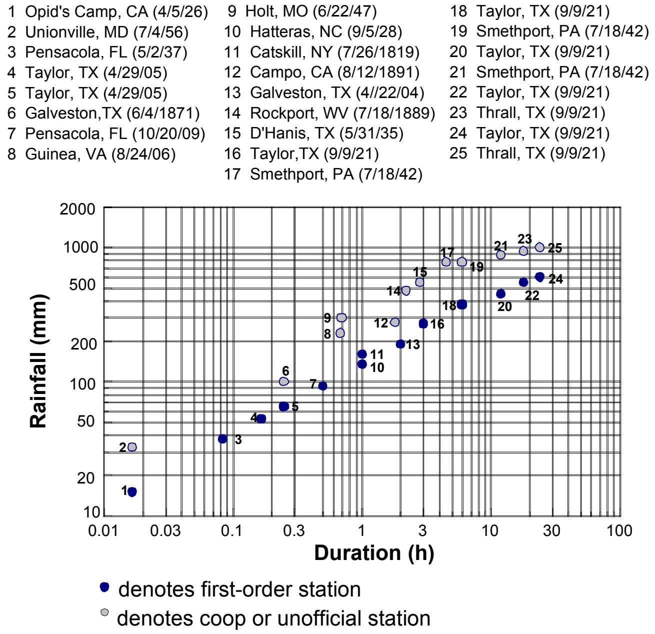


Figure 2.7. Maximum observed rainfalls (U.S.) from USWB, 1947; ECAFE, U.N., 1967

Storm pattern, areal extent, and movement are normally determined by the type of storm (see Section 2.1.2). For example, storms associated with cold fronts (thunderstorms) tend to be more localized, faster moving, and of shorter duration, whereas warm fronts tend to produce slowly moving storms of broad areal extent and longer durations. All three of these factors determine the areal extent of precipitation and how large a portion of the drainage area contributes over time to the surface runoff. As illustrated in Figure 2.9, a small localized storm of a given intensity and duration, occurring over a part of the drainage area, will result in much less runoff than if the same storm covered the entire watershed.

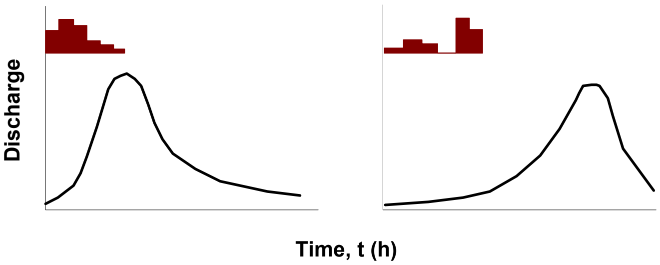


Figure 2.8. Effect of time variation of rainfall intensity on the surface runoff

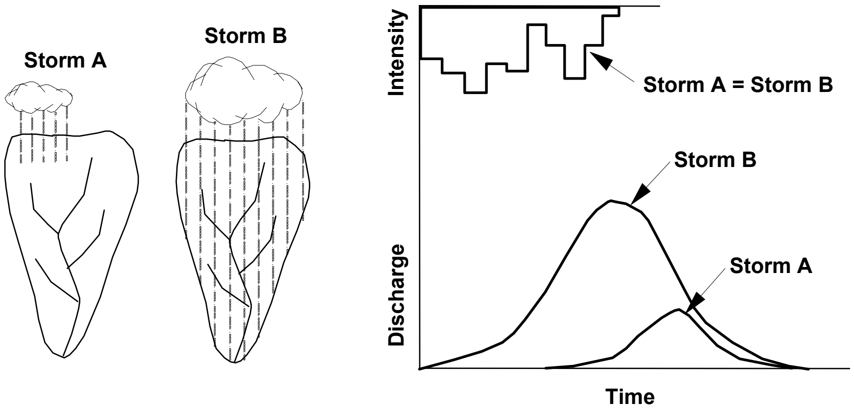


Figure 2.9. Effect of storm size on runoff hydrograph

The location of a localized storm in the drainage basin also affects the time distribution of the surface runoff. A storm near the outlet of the watershed will result in the peak flow occurring very quickly and a rapid passage of the flood. If the same storm occurred in a remote part of the basin, the runoff at the outlet due to the storm would be longer and the peak flow lower due to storage in the channel.

Storm movement has a similar effect on the runoff distribution particularly if the basin is long and narrow. Figure 2.10 shows that a storm moving up a basin from its outlet gives a distribution of runoff that is relatively symmetrical with respect to the peak flow. The same storm moving down the basin will usually result in a higher peak flow and an unsymmetrical distribution with the peak flow occurring later in time.

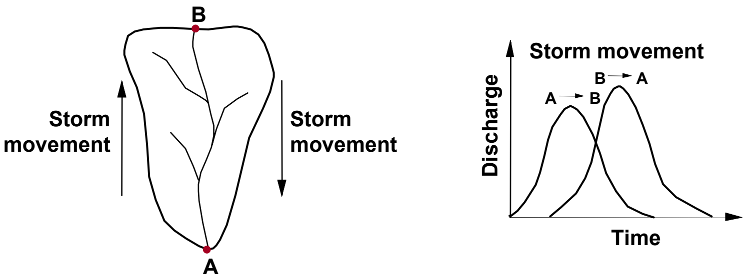


Figure 2.10. Effect of storm movement on runoff hydrograph

Frequency is also an important characteristic because it establishes the frame of reference for how often precipitation with given characteristics is likely to occur. From the standpoint of highway design, a primary concern is with the frequency of occurrence of the resulting surface runoff, and in particular, the frequency of the peak discharge. While the designer is cautioned about assuming that a storm of a given frequency always produces a flood of the same frequency, there are a number of analytical techniques that are based on this assumption, particularly for ungauged watersheds. Some of the factors that determine how closely the frequencies of precipitation and peak discharge correlate with one another are discussed further in Section 2.3.

Precipitation is not easily characterized although there have been many attempts to do so. References and data sources are available that provide general information on the character of precipitation at specified geographic locations. These sources are discussed more fully in Chapter 3. It is important, however, to understand the highly variable and erratic nature of precipitation. Highway designers should become familiar with the different types of storms and the characteristics of precipitation that are indigenous to their regions of concern. They should also understand the seasonal variations that are prevalent in many areas. In addition, it is very beneficial to study reports that have been prepared on historic storms and floods in a region. Such reports can provide information on past storms and the consequences that they may have had on drainage structures.

2.1.4 Intensity-Duration-Frequency Curves

Three rainfall characteristics are important and interact with each other in many hydrologic design problems. Rainfall intensity, duration, and frequency were defined and discussed in the previous section. For use in design, the three characteristics are combined, usually graphically into the intensity-duration-frequency (IDF) curve. Rainfall intensity is graphed as the ordinate and duration as the abscissa. One curve of intensity versus duration is given for each exceedence frequency. IDF curves are location dependent. For example, the IDF curve for Baltimore, MD, is not the same as that for Washington, D.C. The differences, while slight, reflect differences in rainfall characteristics at the two locations. Because of this location dependency, a local IDF curve must be used for hydrologic design work. The development of IDF curves is discussed in Appendix A of HEC-12, Drainage of Highway Pavements (Johnson and Chang, 1984).

IDF curves are plotted on log-log paper and have a characteristic shape. Typically, the IDF curve for a specific exceedence frequency is characteristically curved for small durations, usually 2 hours and shorter, and straight for the longer durations. Thus, the following model can be used to represent the IDF curve for any exceedence frequency:

$$i = \begin{cases} \dfrac{a}{D + b} & \text{for } D \leq 2 \text{ h} \\ cD^{d} & \text{for } D > 2 \text{ h} \end{cases} \tag{2.1}$$

where,

i = rainfall intensity, mm/h (in/h)
D = rainfall duration, h
a, b, c, and d = regression constants.

For D less than 2 hours, a linear least-squares relationship is obtained by taking the reciprocal of the equation, which yields:

$$\frac{1}{i} = \frac{D+b}{a} = \frac{1}{a}D + \frac{b}{a} = fD + g$$

Letting y = 1/i, the values of f and g can be fitted using least-squares regression of y on D. The values of a and b are then obtained by algebraic transformation: a = 1/f and b = g/f. For durations longer than 2 hours, the power-model equation is placed in linear form by taking logarithms:

$$\log i = \log c + d \log D$$

$$y = h + dx$$

in which y = log i, h = log c, and x = log D. Once h and d are fitted with least-squares, the value of c is computed by c = 10^h.

Volume-duration-frequency (VDF) curves are sometimes provided in hydrologic design manuals. The VDF curve is similar to the IDF curve except the depth of rainfall is graphed as the ordinate. The IDF curve is preferred because many design methods use rainfall intensities rather than rainfall depths.

2.2 HYDROLOGIC ABSTRACTIONS

The collective term given to the various processes that act to remove water from the incoming precipitation before it leaves the watershed as runoff is abstractions. These processes are evaporation, transpiration, interception, infiltration, depression storage, and detention storage. The most important abstractions in determining the surface runoff from a given precipitation event are infiltration, depression storage, and detention storage.

2.2.1 Evaporation

Evaporation is the process by which water from the land and water surfaces is converted into water vapor and returned to the atmosphere. It occurs continually whenever the air is unsaturated and temperatures are sufficiently high. Air is 'saturated' when it holds its maximum capacity of moisture at the given temperature. Saturated air has a relative humidity of 100 percent. Evaporation plays a major role in determining the long-term water balance in a watershed. However, evaporation is usually insignificant in small watersheds for single storm events and can be discounted when calculating the discharge from a given rainfall event.

2.2.2 Transpiration

Transpiration is the physical removal of water from the watershed by the life actions associated with the growth of vegetation. In the process of respiration, green plants consume water from the ground and transpire water vapor to the air through their foliage. As was the case with evaporation, this abstraction is only significant when taken over a long period of time, and has minimal effect upon the runoff resulting from a single storm event for a watershed.

2.2.3 Interception

Interception is the removal of water that wets and adheres to objects above ground such as buildings, trees, and vegetation. This water is subsequently removed from the surface through evaporation. Interception can be as high as 2 mm (0.08 in) during a single rainfall event, but usually is nearer 0.5 mm (0.02 in). The quantity of water removed through interception is usually not significant for an isolated storm, but, when added over a period of time, it can be significant.

It is thought that as much as 25 percent of the total annual precipitation for certain heavily forested areas of the Pacific Northwest of the United States is lost through interception during the course of a year.

2.2.4 Infiltration

Infiltration is the flow of water into the ground by percolation through the earth's surface. The process of infiltration is complex and depends upon many factors such as soil type, vegetal cover, antecedent moisture conditions or the amount of time elapsed since the last precipitation event, precipitation intensity, and temperature. Infiltration is usually the single most important abstraction in determining the response of a watershed to a given rainfall event. As important as it is, no generally acceptable model has been developed to accurately predict infiltration rates or total infiltration volumes for a given watershed.

2.2.5 Depression Storage

Depression storage is the term applied to water that is lost because it becomes trapped in the numerous small depressions that are characteristic of any natural surface. When water temporarily accumulates in a low point with no possibility for escape as runoff, the accumulation is referred to as depression storage. The amount of water that is lost due to depression storage varies greatly with the land use. A paved surface will not detain as much water as a recently furrowed field. The relative importance of depression storage in determining the runoff from a given storm depends on the amount and intensity of precipitation in the storm. Typical values for depression storage range from 1 to 8 mm (0.04 to 0.3 in) with some values as high as 15 mm (0.6 in) per event. As with evaporation and transpiration, depression storage is generally not directly calculated in highway design.

2.2.6 Detention Storage

Detention storage is water that is temporarily stored in the depth of water necessary for overland flow to occur. The volume of water in motion over the land constitutes the detention storage. The amount of water that will be stored is dependent on a number of factors such as land use, vegetal cover, slope, and rainfall intensity. Typical values for detention storage range from 2 to 10 mm (0.08 to 0.4 in), but values as high as 50 mm (2 in) have been reported.

2.2.7 Total Abstraction Methods

While the volumes of the individual abstractions may be small, their sum can be hydrologically significant. Therefore, hydrologic methods commonly lump all abstractions together and compute a single value. The SCS curve number method lumps all abstractions together, with the volume equal to the difference between the volumes of rainfall and runoff. The phi-index method assumes a constant rate of abstraction over the duration of the storm. These total abstraction methods simplify the calculation of storm runoff rates.

2.3 CHARACTERISTICS OF RUNOFF

Water that has not been abstracted from the incoming precipitation leaves the watershed as surface runoff. While runoff occurs in several stages, the flow that becomes channelized is the main consideration to highway stream crossing design since it influences the size of a given drainage structure. The rate of flow or runoff at a given instant, in terms of volume per unit of time, is called discharge. Some characteristics of runoff that are important to drainage design are: (1) the peak discharge or peak rate of flow; (2) the discharge variation with time (hydrograph); (3) the stage-discharge relationship; (4) the total volume of runoff; and (5) the frequency with which discharges of specified magnitudes are likely to be equaled or exceeded (probability of exceedence).

2.3.1 Peak Discharge

The peak discharge, often called peak flow, is the maximum rate of runoff passing a given point during or after a rainfall event. Highway designers are interested in peak flows for storms in an area because it is the discharge that a given structure must be sized to handle. Of course, the peak flow varies for each different storm, and it becomes the designer's responsibility to size a given structure for the magnitude of storm that is determined to present an acceptable risk in a given situation. Peak flow rates can be affected by many factors in a watershed, including rainfall, basin size, and the physiographic features.

2.3.2 Time Variation (Hydrograph)

The flow in a stream varies from time to time, particularly during and in response to storm events. As precipitation falls and moves through the watershed, water levels in streams rise and may continue to do so (depending on position of the storm over the watershed) after the precipitation has ceased. The response of an affected stream through time during a storm event is characterized by the flood hydrograph. This response can be pictured by graphing the flow in a stream relative to time. The primary features of a typical hydrograph are illustrated in Figure 2.11 and include the rising and falling limbs, the peak flow, the time to peak, and the time base of the hydrograph. There are several types of hydrographs, such as flow per unit area and stage hydrographs, but all display the same typical variation through time.

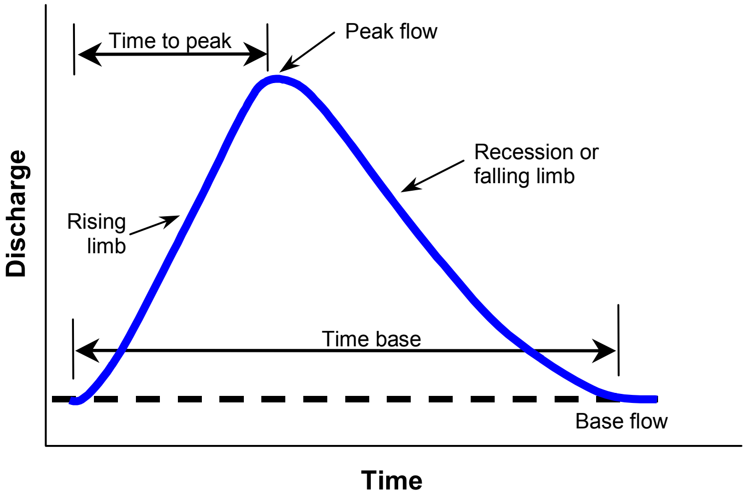


Figure 2.11. Elements of a flood hydrograph

2.3.3 Stage-Discharge

The stage of a river is the elevation of the water surface above some arbitrary datum. The datum can be mean sea level, but can also be set slightly below the point of zero flow in the given stream. The stage of a river is directly related to the discharge, which is the quantity of water passing a given point (see Figure 2.12). As the discharge increases, the stage rises and as the discharge decreases, the stage falls. Generally, discharge is related to stage at a particular point by using a variety of techniques and instrumentation to obtain field measurements of these (and related) parameters.

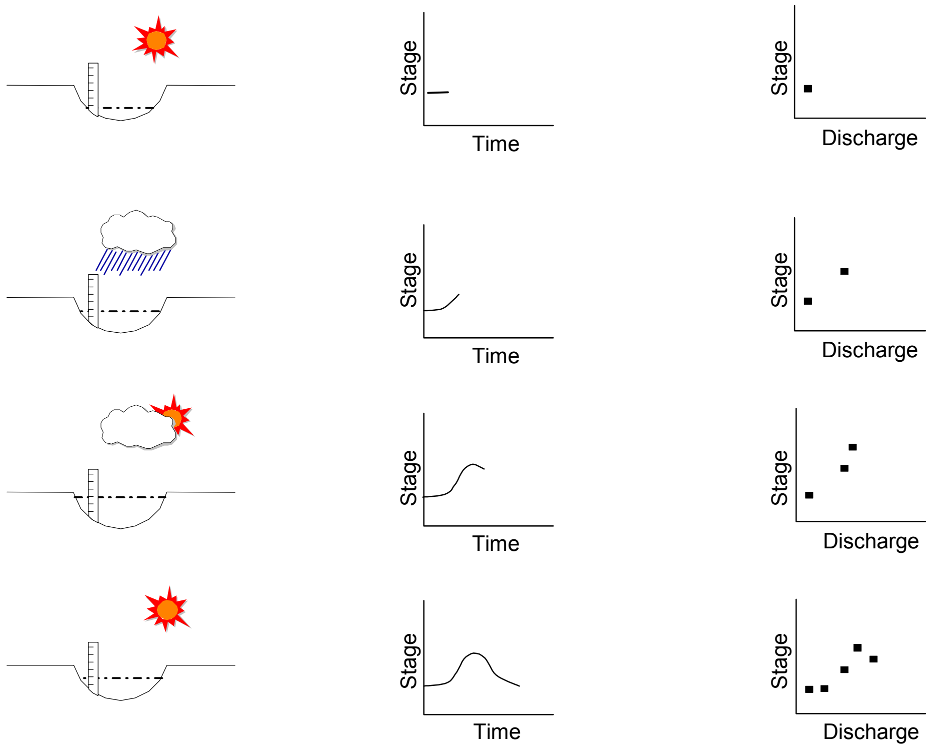


Figure 2.12. Relation between stage and discharge

2.3.4 Total Volume

The total volume of runoff from a given flood is of primary importance to the design of storage facilities and flood control works. Flood volume is not normally a consideration in the design of highway drainage crossing structures. However, flood volume is used in various analyses for other design parameters. Flood volume is most easily determined as the area under the flood hydrograph (Figure 2.11) and is commonly measured in units of cubic meters. The equivalent depth of net rain over the watershed is determined by dividing the volume of runoff by the watershed area.

2.3.5 Frequency

The exceedence frequency is the relative number of times a flood of a given magnitude can be expected to occur on the average over a long period of time. It is usually expressed as a ratio or a percentage. By its definition, frequency is a probabilistic concept and is the probability that a flood of a given magnitude may be equaled or exceeded in a specified period of time, usually 1 year. Exceedence frequency is an important design parameter in that it identifies the level of risk during a specified time interval acceptable for the design of a highway structure.

2.3.6 Return Period

Return period is a term commonly used in hydrology. It is the average time interval between the occurrence of storms or floods of a given magnitude. The exceedence probability (p) and return period (T) are related by:

$$T = \frac{1}{p} \tag{2.2}$$

For example, a flood with an exceedence probability of 0.01 in any one year is referred to as the 100-year flood. The use of the term return period is sometimes discouraged because some people interpret it to mean that there will be exactly T years between occurrences of the event. Two 100-year floods can occur in successive years or they may occur 500 years apart. The return period is only the long-term average number of years between occurrences.

2.4 EFFECTS OF BASIN CHARACTERISTICS ON RUNOFF

The spatial and temporal variations of precipitation and the concurrent variations of the individual abstraction processes determine the characteristics of the runoff from a given storm. These are not the only factors involved, however. Once the local abstractions have been satisfied for a small area of the watershed, water begins to flow overland and eventually into a natural drainage channel such as a gully or a stream valley. At this point, the hydraulics of the natural drainage channels have a large influence on the character of the total runoff from the watershed.

A few of the many factors that determine the hydraulic character of the natural drainage system are drainage area, slope, hydraulic roughness, natural and channel storage, drainage density, channel length, antecedent moisture conditions, urbanization, and other factors. The effect that each of these factors has on the important characteristics of runoff is often difficult to quantify. The following paragraphs discuss some of the factors that affect the hydraulic character of a given drainage system.

2.4.1 Drainage Area

Drainage area is the most important watershed characteristic that affects runoff. The larger the contributing drainage area, the larger will be the flood runoff (see Figure 2.13a). Regardless of the method utilized to evaluate flood flows, peak flow is directly related to the drainage area.

2.4.2 Slope

Steep slopes tend to result in rapid runoff responses to local rainfall excess and consequently higher peak discharges (see Figure 2.13b). The runoff is quickly removed from the watershed, so the hydrograph is short with a high peak. The stage-discharge relationship is highly dependent upon the local characteristics of the cross-section of the drainage channel and, if the slope is sufficiently steep, supercritical flow may prevail. The total volume of runoff is also affected by slope. If the slope is very flat, the rainfall will not be removed as rapidly. The process of infiltration will have more time to affect the rainfall excess, thereby increasing the abstractions and resulting in a reduction of the total volume of rainfall that appears directly as runoff.

Slope is very important in how quickly a drainage channel will convey water and, therefore, it influences the sensitivity of a watershed to precipitation events of various time durations. Watersheds with steep slopes will rapidly convey incoming rainfall and, if the rainfall is convective (characterized by high intensity and relatively short duration), the watershed will respond very quickly with the peak flow occurring shortly after the onset of precipitation. If these convective storms occur with a given frequency, the resulting runoff can be expected to occur with a similar frequency. On the other hand, for a watershed with a flat slope, the response to the same storm will not be as rapid and, depending on a number of other factors, the frequency of the resulting discharge may be dissimilar to the storm frequency.

2.4.3 Hydraulic Roughness

Hydraulic roughness is a composite of the physical characteristics that influence the depth and speed of water flowing across the surface, whether natural or channelized. It affects both the time response of a drainage channel and the channel storage characteristics. Hydraulic roughness has a marked effect on the characteristics of the runoff resulting from a given storm. The peak rate of discharge is usually inversely proportional to hydraulic roughness (i.e., the lower the roughness, the higher the peak discharge). Roughness affects the runoff hydrograph in a manner opposite of slope. The lower the roughness, the more peaked and shorter in time the resulting hydrograph will be for a given storm (see Figure 2.13c).

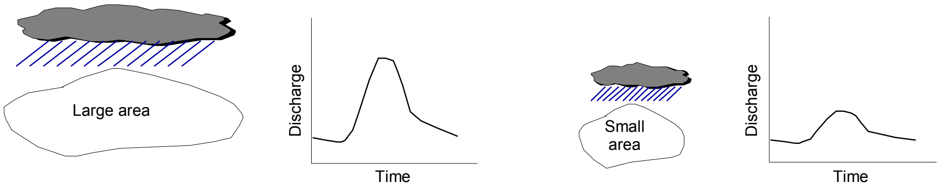
The stage-discharge relationship for a given section of drainage channel is also dependent on roughness (assuming normal flow conditions and the absence of artificial controls). A higher roughness results in a higher stage for a given discharge.

The total volume of runoff is virtually independent of hydraulic roughness. An indirect relationship does exist in that higher roughness slows the watershed response and allows some of the abstraction processes more time to affect runoff. Roughness also has an influence on the frequency of discharges of certain magnitudes by affecting the response time of the watershed to precipitation events of specified frequencies.

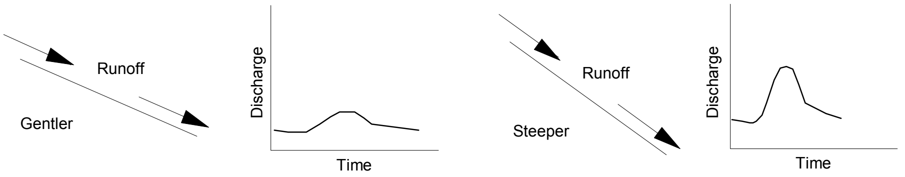
2.4.4 Storage

It is common for a watershed to have natural or manmade storage that greatly affects the response to a given precipitation event. Common features that contribute to storage within a watershed are lakes, marshes, heavily vegetated overbank areas, natural or manmade constrictions in the drainage channel that cause backwater, and the storage in the floodplains of large, wide rivers. Storage can have a significant effect in reducing the peak rate of discharge, although this reduction is not necessarily universal. There have been some instances where artificial storage redistributes the discharges very radically, resulting in higher peak discharges than would have occurred had the storage not been added. As shown in Figure 2.13d, storage generally spreads the hydrograph out in time, delays the time to peak, and alters the shape of the resulting hydrograph from a given storm. The effect of storage reservoirs is detailed in Section 7.2.

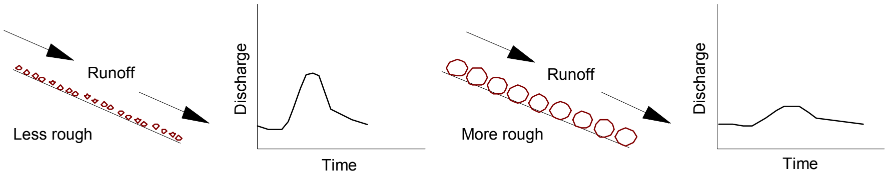
(a) Relationship of discharge and area



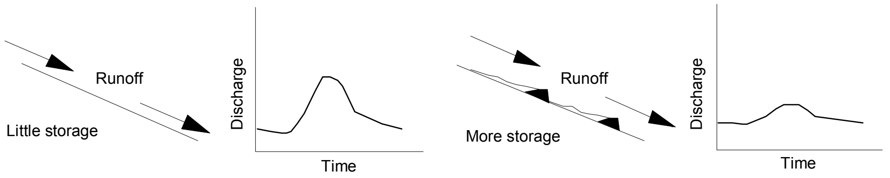
(b) Relationship of discharge and slope



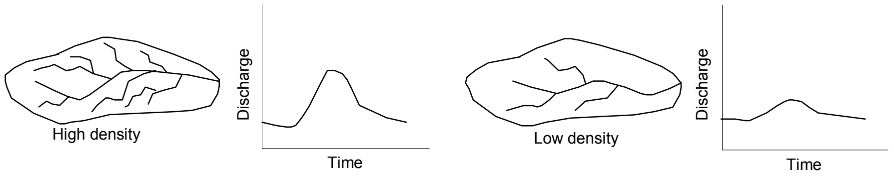
(c) Relationship of discharge and roughness



(d) Relationship of discharge and storage



(e) Relationship of discharge and drainage density



(f) Relationship of discharge and channel length

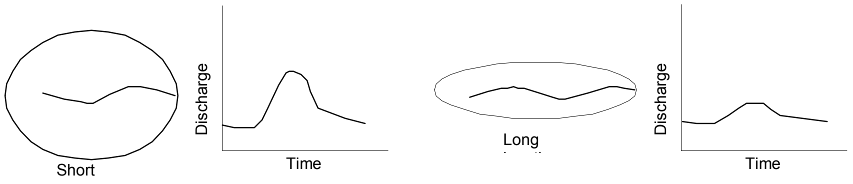


Figure 2-13. Effects of basin characteristics on the flood hydrograph

The stage-discharge relationship also can be influenced by storage within a watershed. If the section of a drainage channel is upstream of the storage and within the zone of backwater, the stage for a given discharge will be higher than if the storage were not present. If the section is downstream of the storage, the stage-discharge relationship may or may not be affected, depending upon the presence of channel controls.

The total volume of runoff is not directly influenced by the presence of storage. Storage will redistribute the volume over time, but will not directly change the volume. By redistributing the runoff over time, storage may allow other abstraction processes to decrease the runoff (as was the case with slope and roughness).

Changes in storage have a definite effect upon the frequency of discharges of given magnitudes. Storage tends to dampen the response of a watershed to very short events and to accentuate the response to very long events. This alters the relationship between frequency of precipitation and the frequency of the resultant runoff.

2.4.5 Drainage Density

Drainage density can be defined as the ratio between the number of well-defined drainage channels and the total drainage area in a given watershed. Drainage density is usually assumed to equal the total length of continuously flowing streams divided by the drainage area. It is determined by the topography and the geography of the watershed.

Drainage density has a strong influence on both the spatial and temporal response of a watershed to a given precipitation event. If a watershed is well covered by a pattern of interconnected drainage channels, and the overland flow time is relatively short, the watershed will respond more rapidly than if it were sparsely drained and overland flow time was relatively long. The mean velocity of runoff is normally lower for overland flow than it is for flow in a well-defined natural channel. High drainage densities are associated with increased response of a watershed leading to higher peak discharges and shorter hydrographs for a given precipitation event (see Figure 2.13e).

Drainage density has a minimal effect on the stage-discharge relationship for a particular section of drainage channel. It does, however, have an effect on the total volume of runoff since some of the abstraction processes are directly related to how long the rainfall excess exists as overland flow. Therefore, the lower the density of drainage, the lower will be the volume of runoff from a given precipitation event.

Changes in drainage density such as with channel improvements in urbanizing watersheds can have an effect on the frequency of discharges of given magnitudes. By strongly influencing the response of a given watershed to any precipitation input, the drainage density determines in part the frequency of the response. The higher the drainage density, the more closely related the resultant runoff frequency would be to that of the corresponding precipitation event.

2.4.6 Channel Length

Channel length is an important watershed characteristic. The longer the channel, the more time it takes for water to be conveyed from the headwaters of the watershed to the outlet. Consequently, if all other factors are the same, a watershed with a longer channel length will usually have a slower response to a given precipitation input than a watershed with a shorter channel length. As the hydrograph travels along a channel, it is attenuated and extended in time due to the effects of channel storage and hydraulic roughness. As shown in Figure 2.13f, longer channels result in lower peak discharges and longer hydrographs.

The frequency of discharges of given magnitudes will also be influenced by channel length. As was the case for drainage density, channel length is an important parameter in determining the response time of a watershed to precipitation events of given frequency. However, channel length may not remain constant with discharges of various magnitudes. In the case of a wide floodplain where the main channel meanders appreciably, it is not unusual for the higher flood discharges to overtop the banks and essentially flow in a straight line in the floodplain, thus reducing the effective channel length.

The stage-discharge relationship and the total volume of runoff are practically independent of channel length. Volume, however, will be redistributed in time, similar in effect to storage but less pronounced.

2.4.7 Antecedent Moisture Conditions

As noted earlier, antecedent moisture conditions, which are the soil moisture conditions of the watershed at the beginning of a storm, affect the volume of runoff generated by a particular storm event. Runoff volumes are related directly to antecedent moisture levels. The smaller the moisture in the ground at the beginning of precipitation, the lower will be the runoff. Conversely, the larger the moisture content of the soil, the higher the runoff attributable to a particular storm.

2.4.8 Urbanization

As a watershed undergoes urbanization, the peak discharge typically increases and the hydrograph becomes shorter and rises more quickly. This is due mostly to the improved hydraulic efficiency of an urbanized area. In its natural state, a watershed will have developed a natural system of conveyances consisting of gullies, streams, ponds, marshes, etc., all in equilibrium with the naturally existing vegetation and physical watershed characteristics. As an area develops, typical changes made to the watershed include: (l) removal of existing vegetation and replacement with impervious pavement or buildings, (2) improvement to natural watercourses by channelization, and (3) augmentation of the natural drainage system by storm sewers and open channels. These changes tend to decrease depression storage, infiltration rates, and travel time. Consequently, peak discharges increase, with the time base of hydrographs becoming shorter and the rising limb rising more quickly.

2.4.9 Other Factors

There can be other factors within the watershed that determine the characteristics of runoff, including the extent and type of vegetation, the presence of channel modifications, and flood control structures. These factors modify the runoff by either augmenting or negating some of the basin characteristics described above. It is important to recognize that all of the factors discussed exist concurrently within a given watershed, and their combined effects are very difficult to model and quantify.

2.5 ILLUSTRATION OF THE RUNOFF PROCESS

In Section 2.2, several key hydrologic abstractions were described in general terms. The method by which the runoff process can be analyzed and the results used to obtain a hydrograph are illustrated in this section. Figures 2.14a through 2.14f show the development of the flood hydrograph from a typical rainfall event.

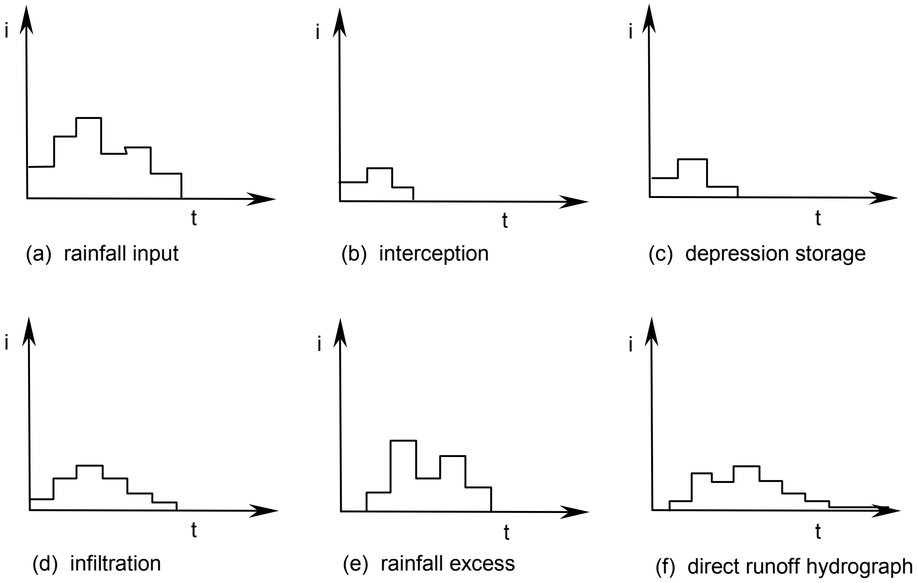


Figure 2.14. The runoff process

2.5.1 Rainfall Input

Rainfall is randomly distributed in time and space, and the rainfall experienced at a particular point can vary greatly. For simplification, consider the rainfall at only one point in space and assume that the variation of rainfall intensity with time can be approximated by discrete time periods of constant intensity. This simplification is illustrated in Figure 2.14a. The specific values of intensity and time are not important for this illustrative example since it shows only relative magnitudes and relationships. The rainfall, so arranged, is the input to the runoff process, and from this, the various abstractions must be deleted.

2.5.2 Interception

Figure 2.14b illustrates the relative magnitude and time relationship for interception. When the rainfall first begins, the foliage and other intercepting surfaces are dry. As water adheres to these surfaces, a large portion of the initial rainfall is abstracted. This occurs in a relatively short period of time and, once the initial wetting is complete, the interception losses quickly decrease to a lower, nearly constant value. The rainfall that has not been intercepted falls to the ground surface to continue in the runoff process.

2.5.3 Depression Storage

Figure 2.14c illustrates the relative magnitude of depression storage with time. Only the water that is in excess of that necessary to supply the interception is available for depression storage. This is the reason that the depression-storage curve begins at zero. The amount of water that goes into depression storage varies with differing land uses and soil types, but the curve shown is representative. The smallest depressions are filled first and then the larger depressions are filled as time and the rainfall supply continue. The slope of the depression-storage curve depends on the distribution of storage volume with respect to the size of depressions. There are usually many small depressions that fill rapidly and account for most of the total volume of depression storage. This results in a rapid peaking of storage with time as shown in Figure 2.14c. The large depressions take longer to fill and the curve gradually approaches zero when all of the depression storage has been filled. When the rainfall input equals the interception, infiltration, and depression storage, there is no surface runoff.

2.5.4 Infiltration

Infiltration is a complex process, and the rate of infiltration at any point in time depends on many factors. The important point to be illustrated in Figure 2.14d is the time dependence of the infiltration curve. It is also important to note the behavior of the infiltration curve after the period of relatively low rainfall intensity near the middle of the storm event. The infiltration rate increases over what it was prior to the period of lower intensity because the upper layers of the soil are drained at a rate that is independent of the rainfall intensity. Most deterministic models, including the phi-index method for estimating infiltration discussed in Section 6.1.4.3, do not model the infiltration process accurately in this respect.

2.5.5 Rainfall Excess

Only after interception, depression storage, and infiltration have been satisfied is there an excess of water available to run off from the land surface. As previously defined, this is the rainfall excess and is illustrated in Figure 2.14e. Note how this rainfall excess differs with the actual rainfall input, Figure 2.14a.

The concept of excess rainfall is very important in hydrologic analyses. It is the amount of water available to run off after the initial abstractions and other losses have been satisfied. Except for the losses that may occur during overland and channelized flow, it determines the volume of water that flows past the outlet of a drainage basin. When multiplied by the drainage area, it should be very nearly equal to the volume under the direct runoff hydrograph. The rainfall excess has a direct effect on the outflow hydrograph. It influences the magnitude of the peak flow, the duration of the flood hydrograph, and the shape of the hydrograph.

2.5.6 Detention Storage

A volume of water is detained in temporary (detention) storage. This volume is proportional to the local rainfall excess and is dependent on a number of other factors as mentioned in Section 2.2.6. Although all water in detention storage eventually leaves the basin, this requirement must be met before runoff can occur.

2.5.7 Local Runoff

Local runoff is actually the residual of the rainfall input after all abstractions have been satisfied. It is similar in shape to the excess rainfall (see Figure 2.14e), but is extended in time as the detention storage acts on the local runoff.

2.5.8 Outflow Hydrograph

Figure 2.14f illustrates the final outflow hydrograph from the watershed due to the local runoff hydrograph. This final hydrograph is the cumulative effect of all the modifying factors that act on the water as it flows through drainage channels as discussed in Section 2.4. The total volume of water contained under the direct runoff hydrograph of Figure 2.14f and the rainfall excess of

Figure 2.14e are the same, although the position of the outflow hydrograph in time is modified due to the smoothing of the surface runoff and the channel processes.

The processes that have been discussed in the previous sections all act simultaneously to transform the incoming rainfall from that shown in Figure 2.14a to the corresponding outflow hydrograph of Figure 2.14f. This example serves to illustrate the runoff process for a small local area. If the watershed is of appreciable size or if the storm is large, areal and time variations and other factors add a new level of complexity to the problem.

2.6 TRAVEL TIME

The travel time of runoff is very important in hydrologic design. In the design of inlets and pipe drainage systems, travel times of surface runoff must be estimated. Some peak discharge methods (Chapter 5) use the time of concentration as input to obtain rainfall intensities from the intensity-duration-frequency curves. Hydrograph times-to-peak, which are in some cases computed from times of concentration, are used with hydrograph methods (Chapter 6). Channel routing methods (Chapter 7) use computed travel times in routing hydrographs through channel reaches. Thus, estimating travel times are central to a variety of hydrologic design problems.

2.6.1 Time of Concentration

The time of concentration, which is denoted as t_c, is defined as the time required for a particle of water to flow from the hydraulically most distant point in the watershed to the outlet or design point. Factors that affect the time of concentration are the length of flow, the slope of the flow path, and the roughness of the flow path. For flow at the upper reaches of a watershed, rainfall characteristics, most notably the intensity, may also influence the velocity of the runoff.

Various methods can be used to estimate the time of concentration of a watershed. When selecting a method to use in design, it is important to select a method that is appropriate for the flow path. Some estimation methods were designed and can be classified as “lumped” in that they were designed and calibrated to be used for an entire watershed; the SCS lag formula is an example of this method. These methods have t_c as the dependent variable. Other methods are intended for one segment of the principal flow path and produce a flow velocity that can be used with the length of that segment of the flow path to compute the travel time on that segment. With this method, the time of concentration equals the sum of the travel times on each segment of the principal flow path.

In classifying these methods so that the proper method can be selected, it is useful to describe the segments of flow paths. Sheet flow occurs in the upper reaches of a watershed. Such flow occurs over short distances and at shallow depths prior to the point where topography and surface characteristics cause the flow to concentrate in rills and swales. The depth of such flow is usually 20 to 30 mm (0.8 to 1.2 in) or less. Concentrated flow is runoff that occurs in rills and swales and has depths on the order of 40 to 100 mm (1.6 to 3.9 in). Part of the principal flow path may include pipes or small streams. The travel time through these segments would be computed separately. Velocities in open channels are usually determined assuming bank-full depths.

2.6.2 Velocity Method

The velocity method (sometimes referred to as the segment method) can be used to estimate travel times for sheet flow, shallow concentrated flow, pipe flow, or channel flow. It is based on estimating the travel time from the length and velocity:

$$T_t = \frac{L}{60V} \tag{2.3}$$

where,

T_t = travel time, min
L = flow length, m (ft)
V = flow velocity, m/s (ft/s).

The travel time is computed for the principal flow path. When the principal flow path consists of segments that have different slopes or land covers, the principal flow path should be divided into segments and Equation 2.3 used for each flow segment. The time of concentration is then the sum of travel times:

$$t_c = \sum_{i=1}^{k} T_{t_i} = \sum_{i=1}^{k} \left(\frac{L_i}{60 V_i} \right) \tag{2.4}$$

where,

k = number of segments
i = subscript referring to each flow segment.

Velocity is a function of the type of flow (overland, sheet, rill and gully flow, channel flow, pipe flow), the roughness of the flow path, and the slope of the flow path. Some methods also include a rainfall index such as the 2-year, 24-hour rainfall depth. A number of methods have been developed for estimating the velocity.

2.6.2.1 Sheet-Flow Travel Time

Sheet flow is a shallow mass of runoff on a plane surface with the depth uniform across the sloping surface. Typically flow depths will not exceed 50 mm (2 in). Such flow occurs over relatively short distances, rarely more than about 90 m (300 ft), but most likely less than 25 m (80 ft). Sheet flow rates are commonly estimated using a version of the kinematic wave equation. The original form of the kinematic wave time of concentration is:

$$t_c = \frac{\alpha}{i^{0.4}} \left(\frac{nL}{\sqrt{S}} \right)^{0.6} \tag{2.5}$$

where,

t_c = time of concentration, min
n = roughness coefficient (see Table 2.1)
L = flow length, m (ft)
i = rainfall intensity, mm/h (in/h), for a storm that has a return period T and duration of t_c minutes
S = slope of the surface, m/m (ft/ft)
α = unit conversion constant equal to 6.9 in SI units and 0.93 in CU units.

Some hydrologic design methods, such as the rational equation, assume that the storm duration equals the time of concentration. Thus, the time of concentration is entered into the IDF curve to find the design intensity. However, for Equation 2.5, i depends on t_c and t_c is not initially known. Therefore, the computation of t_c is an iterative process. An initial estimate of t_c is assumed and used to obtain i from the intensity-duration-frequency curve for the locality. The t_c is computed from Equation 2.5 and used to check the initial value of i. If they are not the same, the process is repeated until two successive t_c estimates are the same.

Table 2.1. Manning's Roughness Coefficient (n) for Overland and Sheet Flow

(SCS, 1986; McCuen, 1989)

n	**Surface Description**
0.011	Smooth asphalt
0.012	Smooth concrete
0.013	Concrete lining
0.014	Good wood
0.014	Brick with cement mortar
0.015	Vitrified clay
0.015	Cast iron
0.024	Corrugated metal pipe
0.024	Cement rubble surface
0.050	Fallow (no residue)
	Cultivated soils
0.060	Residue cover ≤ 20%
0.170	Residue cover > 20%
0.130	Range (natural)
	Grass
0.150	Short grass prairie
0.240	Dense grasses
0.410	Bermuda grass
	Woods*
0.400	Light underbrush
0.800	Dense underbrush

*When selecting n for woody underbrush, consider cover to a height of about 30 mm (0.1 ft). This is the only part of the plant cover that will obstruct sheet flow.

To avoid the necessity to solve for t_c iteratively, the SCS TR-55 (1986) uses the following variation of the kinematic wave equation:

$$t_c = \frac{\alpha}{P_2^{0.5}} \left(\frac{nL}{\sqrt{S}} \right)^{0.8} \tag{2.6}$$

where,

P_2 = 2-year, 24-hour rainfall depth, mm (in)

α = unit conversion constant equal to 5.5 in SI units and 0.42 in CU units.

The other variables are as previously defined. Equation 2.6 is based on an assumed IDF relationship. SCS TR-55 (1986) recommends an upper limit of L = 90 m (300 ft) for using this equation.

2.6.2.2 Shallow Concentrated Flow

After short distances, sheet flow tends to concentrate in rills and then gullies of increasing proportions. Such flow is usually referred to as shallow concentrated flow. The velocity of such flow can be estimated using an empirical relationship between the velocity and the slope:

$$V = \alpha k S^{0.5} \tag{2.7}$$

where,

V = velocity, m/s (ft/s)
S = slope, m/m (ft/ft)
k = dimensionless function of land cover (see Table 2.2)
α = unit conversion constant equal to 10 in SI and 33 in CU units.

Table 2.2. Intercept Coefficients for Velocity vs. Slope Relationship (McCuen, 1989)

k	Land Cover/Flow Regime
0.076	Forest with heavy ground litter; hay meadow (overland flow)
0.152	Trash fallow or minimum tillage cultivation; contour or strip cropped; woodland (overland flow)
0.213	Short grass pasture (overland flow)
0.274	Cultivated straight row (overland flow)
0.305	Nearly bare and untilled (overland flow); alluvial fans in western mountain regions
0.457	Grassed waterway (shallow concentrated flow)
0.491	Unpaved (shallow concentrated flow)
0.619	Paved area (shallow concentrated flow); small upland gullies

2.6.2.3 Pipe and Channel Flow

Flow in gullies empties into channels or pipes. In many cases, the transition between shallow concentrated flow and open channels may be assumed to occur where either the blue-line stream is depicted on USGS quadrangle sheets (scale equals 1:24000) or when the channel is visible on aerial photographs. Channel lengths may be measured directly from the map or scale photograph. However, depending on the scale of the map and the sinuosity of the channel, a map-derived channel length may be an underestimate. Pipe lengths should be taken from as-built drawings for existing systems and design plans for future systems.

Cross-section information (i.e., depth-area and roughness) can be obtained for any channel reach in the watershed. Manning's equation can be used to estimate average flow velocities in pipes and open channels:

$$V = \frac{\alpha}{n} R^{2/3} S^{1/2} \tag{2.8}$$

where,

V = velocity, m/s (ft/s)
n = Manning's roughness coefficient
R = hydraulic radius, m (ft)

S = slope, m/m (ft/ft)
α = unit conversion constant equal to 1.0 in SI units and 1.49 in CU units.

The hydraulic radius equals the cross-sectional area divided by the wetted perimeter. For a circular pipe flowing full, the hydraulic radius equals one-fourth of the diameter: R = D/4. For flow in a wide rectangular channel, the hydraulic radius is approximately equal to the depth of flow (d): R = d.

Example 2.1: Estimating Time of Concentration with the Velocity Method. Two watershed conditions are indicated, pre- and post-development, and summarized in Table 2.3. In the pre-development condition, the 1.62-hectare (4-acre) drainage area is primarily forested, with a natural channel having a good stand of high grass. In the post-development condition, the channel has been eliminated and replaced with a 380-mm (15-inch) diameter pipe. The solution using SI follows; the process is identical in CU units, but is not included here because the example is straightforward.

For the existing condition, the velocities of flow for the overland and grassed waterway segments can be obtained with Equation 2.7 and Table 2.2. For the slopes given in Table 2.3, the velocities for the first two segments are:

$$V_1 = \alpha k S^{0.5} = 10\,(0.076)(0.01)^{0.5} = 0.076 \text{ m/s}$$

$$V_2 = \alpha k S^{0.5} = 10\,(0.457)(0.008)^{0.5} = 0.409 \text{ m/s}$$

$$V_3 = \frac{1.0}{0.15}\,(0.3)^{0.67}(0.008)^{0.5} = 0.270 \text{ m/s}$$

For the roadside channel, the velocity can be estimated using Manning's equation; a value for Manning's n of 0.15 is obtained from Table 2.1 and a hydraulic radius of 0.3 m is estimated using conditions at the site:

Table 2.3. Characteristics of Principal Flow Path for Example 2.1

Watershed Condition	Flow Segment	Length (m)	Slope (m/m)	Type of Flow
Existing	1	43	0.010	Overland (forest)
	2	79	0.008	Grassed waterway
	3	146	0.008	Roadside channel (high grass, good stand)
Developed	1	15	0.010	Overland (short grass)
	2	15	0.010	Paved
	3	91	0.008	Grassed waterway
	4	128	0.009	Pipe-concrete (D = 380 mm)

Thus the time of concentration can be computed with Equation 2.4:

$$t_c = \frac{43}{0.076} + \frac{79}{0.409} + \frac{146}{0.27} = 566 + 193 + 541 = 1300 \text{ s} \approx 22 \text{ min}$$

For the post-development conditions, the flow velocities for the first three segments can be determined with Equation 2.7. For the slopes given in Table 2.3, the velocities are:

$$V_1 = 10(0.213)(0.01)^{0.5} = 0.213 \text{ m/s}$$
$$V_2 = 10(0.619)(0.01)^{0.5} = 0.619 \text{ m/s}$$
$$V_3 = 10(0.457)(0.008)^{0.5} = 0.409 \text{ m/s}$$

Assuming Manning's coefficient equals 0.011 for the concrete pipe and R = D/4, the velocity is:

$$V = \frac{1.0}{0.011}\left(\frac{0.38}{4}\right)^{0.67}(0.009)^{0.5} = 1.8 \text{ m/s}$$

A slope of 0.009 m/m is used since the meandering roadside channel was replaced with a pipe, which resulted in a shorter length of travel and, therefore, a steeper slope. Thus the time of concentration is:

$$t_c = \frac{15}{0.213} + \frac{15}{0.619} + \frac{91}{0.409} + \frac{128}{1.8}$$

$$= 70 + 24 + 222 + 71 = 387 \text{ s} \approx 6 \text{ min}$$

Thus the land development decreased the time of concentration from 22 minutes to 6 minutes.

Example 2.2: Iterative Calculations Using the Kinematic Sheet Flow Equation. Consider the case of overland flow on short grass (n = 0.15) at a slope of 0.005 m/m. Assume the flow length is 50 m. The solution using SI follows; the process is identical in CU units. Equation 2.5 is:

$$t_c = \frac{6.9}{i^{0.4}}\left(\frac{0.15(50)}{\sqrt{0.005}}\right)^{0.6} = \frac{113}{i^{0.4}}$$

The value of i is obtained from an IDF curve for the locality of the project. For this example, the IDF curve of Baltimore is used (see Figure 2.15), and the problem assumes that a 2-year return period is specified. An initial t_c of 12 minutes will be used to obtain the intensity from Figure 2.15. The initial intensity is 116 mm/h. Using the above equation gives a t_c of 17minutes. Since this differs from the assumed t_c of 12 minutes, a second iteration is necessary.

Using a duration of 17 minutes with Figure 2.15 gives a rainfall intensity of 78 mm/h, which, when substituted into the equation, yields an estimated t_c of 20 minutes. Once again, this differs from the assumed value of 17 minutes, so another iteration is required.

For this iteration, the rainfall intensity is found from Figure 2.15 using a duration of 20 minutes. This gives an intensity of 72 mm/h. With the equation, the estimated t_c is again 20 minutes. Therefore, a time of concentration of 20 minutes is used for this flow path.

Example 2.3: Time of Concentration with Iterative Sheet Flow Computations. Figure 2.16a shows the principal flow path for the existing conditions of a small watershed. The characteristics of each section are given in Table 2.4, including the land use/cover, slope, and length. The solution using SI follows; the process is identical in CU units.

The shallow concentrated flow equation is used to compute the velocity of flow for section AB:

$$V = \alpha k S^{0.5} = 10\left(0.076\right)\left(0.07\right)^{0.5} = 0.2\ m/s$$

Thus, the travel time is:

$$T_t = \frac{150\ m}{0.2\ m/s\ \left(60\right)} = 12\ min$$

For the section BC, Manning's equation is used. For a trapezoidal channel, the hydraulic radius is:

$$R = \frac{A}{P} = \frac{w d + z d^2}{w + 2d\sqrt{1 + z^2}} + \frac{0.3(0.7) + 2(0.7)^2}{0.3 + 2(0.7)\sqrt{1 + (2)^2}} = 0.35\ m$$

Thus, Manning's equation yields a velocity of:

$$V = \frac{1}{0.040}\left(0.35\right)^{0.67}\left(0.012\right)^{0.5} = 1.36\ m/s$$

and the travel time is:

$$T_t = \frac{1050\ m}{1.36\ m/s\left(60\right)} = 13\ min$$

Table 2.4. Characteristics of Principal Flow Path for Example 2.3

Watershed Condition	Flow Segment	Length (m)	Slope (m/m)	n	Land Use/Land Cover
Existing	A to B	150	0.07	-	Overland (forest)
	B to C	1050	0.012	0.040	Natural channel (trapezoidal): w = 0.3m, d = 0.7 m, z = 2:1
	C to D	1100	0.006	0.030	Natural channel (trapezoidal): w = 1.25 m, d= 0.7 m, z = 2:1
Developed	E to F	25	0.07	0.013	Sheet flow: i = 47/(0.285 + D) where i[=] mm/h, D[=] h
	F to G	125	0.07	-	Grassed swale
	G to H	275	0.02	-	Paved area
	H to J	600	0.015	0.015	Storm drain (D = 1050 mm)
	J to K	900	0.005	0.019	Open channel (trapezoidal): w = 1.6 m, d = 1 m, z = 1:1

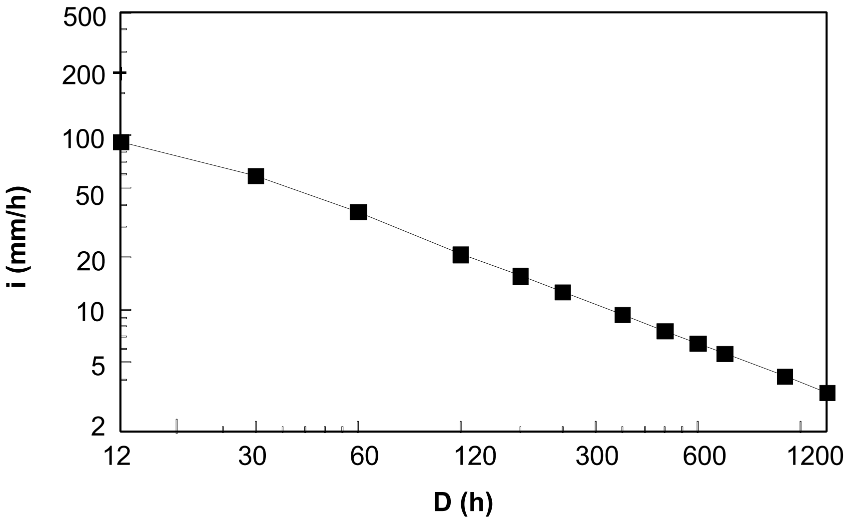
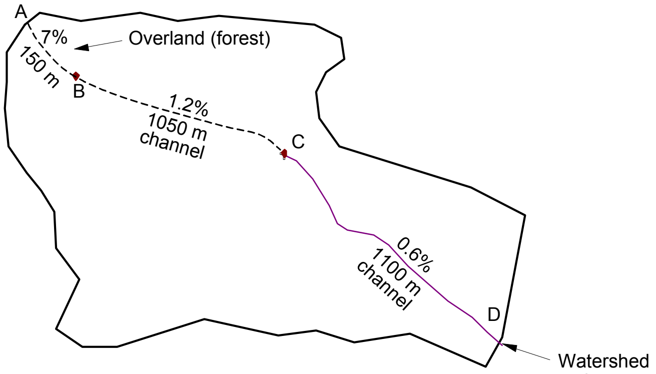
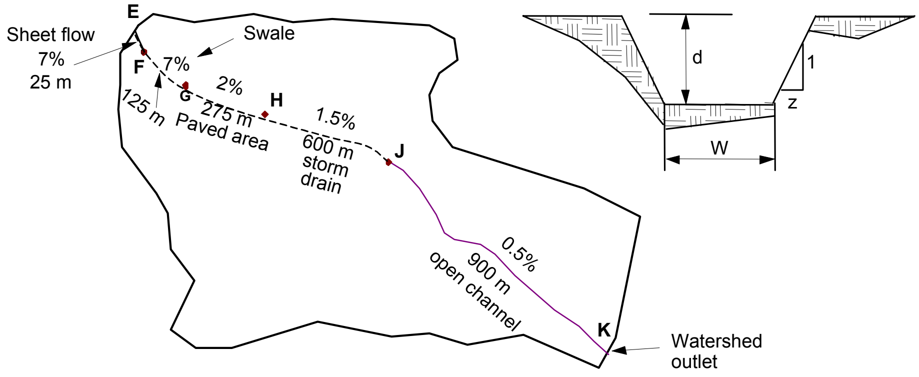


Figure 2.15. Rainfall intensity-duration-frequency curves for selected return periods



(a) principal flow path for existing conditions



(b) principal flow path for developed conditions

Figure 2.16. Time of concentration estimation

For the section CD, Manning's equation is used. The hydraulic radius is:

$$R = \frac{1.25(0.7) + 2(0.7)^2}{1.25 + 2(0.7)\sqrt{1 + (2)^2}} = 0.42 \ m$$

Thus, the velocity is:

$$V = \frac{1}{0.030}(0.42)^{0.67}(0.006)^{0.5} = 1.45 \ m/s$$

and the travel time is:

$$T_t = \frac{1100 \ m}{1.45 \ m/s(60)} = 13 \ min$$

Thus, the total travel time is the sum of the travel times for the individual segments (Equation 2.4):

$$t_c = 12 + 13 + 13 = 38 \ min$$

For the developed conditions, the principal flow path is segmented into five parts (see Figure 2.16b). For the first part of the overland flow portion, the section from E to F, the runoff is sheet flow; thus, the kinematic wave equation (Equation 2.6) is used. Since this is an iterative equation and we will use an intensity associated with the time of concentration for the watershed, we will calculate the travel time for this segment last.

For the section FG, the flow path consists of grass-lined swales. Equation 2.7 can be used to compute the velocity:

$$V = \alpha k S^{0.5} = 10(0.457)(0.07)^{0.5} = 1.21 \ m/s$$

Thus, the travel time is:

$$T_t = \frac{L}{60V} = \frac{125 \ m}{1.21 \ m/s(60)} = 2 \ min$$

For the segment GH, the principal flow path consists of paved gutters. Thus, Equation 2.7 with Table 2.2 is used:

$$V = \alpha k S^{0.5} = 10(0.619)(0.02)^{0.5} = 0.88 \ m/s$$

and the travel time is:

$$T_t = \frac{L}{60 \ V} = \frac{275 \ m}{0.88 \ m/s(60)} = 5 \ min$$

The segment HJ is a 1050-mm (nominally 42-inch) pipe. Thus, Manning's equation is used. The hydraulic radius is one-fourth the diameter (D/4), so the velocity for full flow is:

$$V = \frac{1}{0.015}(0.2625)^{0.67}(0.015)^{0.5} = 3.35 \ m/s$$

and the travel time is:

$$T_t = \frac{L}{60V} = \frac{600 \ m}{3.35 \ m/s(60)} = 3 \ min$$

The final section JK is an improved trapezoidal channel. The hydraulic radius is:

$$R = \frac{w\,d + z\,d^2}{w + 2d\sqrt{1+z^2}} = \frac{1.6(1) + 1(1)^2}{1.6 + 2(1)\sqrt{1+1^2}} = 0.59 \ m$$

Manning's equation is used to compute the velocity:

$$V = \frac{1}{0.019}(0.59)^{0.67}(0.005)^{0.5} = 2.61 \ m/s$$

and the travel time is:

$$T_t = \frac{L}{60\,V} = \frac{900 \ m}{2.61 \ m/s\,(60)} = 6 \ min$$

Thus, the total travel time through the four segments (excluding the first segment) is:

$$t_c = \sum T_t = 2 + 5 + 3 + 6 = 16 \ min$$

Therefore, we know that the time of concentration will be 16 min plus the time of travel over the sheet flow segment EF. For short durations at the location of this example, the 2-year IDF curve is represented by the following relationship between i and D:

$$i = \frac{47}{0.285 + D}$$

where,

i = intensity, mm/h
D = duration, h.

Iteration 1: Assume that travel time on the sheet flow segment is 2 minutes. Therefore, t_c = D = 16 + 2 = 18 min. The 2-year IDF curve is used to estimate the intensity:

$$i = \frac{47}{0.285 + D} = \frac{47}{0.285 + 18/60} = 80 \ mm/h$$

Consequently, Equation 2.6 yields an estimate of the travel time:

$$T_t = \frac{6.9}{80^{0.4}}\left(\frac{0.013(25)}{\sqrt{0.07}}\right)^{0.6} = 1 \ min$$

Since we assumed 2 min for this segment, a second iteration will be performed using the new estimate.

Iteration 2: Assume $t_c = D = 16 + 1 = 17$ min

$$i = \frac{47}{0.285 + 17/60} = 83 \ mm/h$$

$$T_t = \frac{6.9}{83^{0.4}} \left(\frac{0.013(25)}{\sqrt{0.07}} \right)^{0.6} = 1 \ min$$

The change in rainfall intensity did not change the travel time for this segment (rounded to the nearest minute); therefore, the computations are completed. The time of concentration for the post-developed condition is 17 min. This t_c is 45 percent of the t_c for the existing conditions.