7 Hydrology

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7 Hydrology

7.1 OVERVIEW

7.1.1 Introduction

Hydrology is defined as the science of the interrelationship between water on and under the ground, and in the atmosphere. For the purpose of this manual, hydrology will deal with estimating flood magnitudes as the result of precipitation. In the design of highway drainage structures, floods are usually considered in terms of peak runoff or discharge in cubic feet per second, and hydrographs as discharge-versus-time. If structures are designed to control volume of runoff, like detention storage facilities, or if flood routing through culverts is used, then the entire discharge hydrograph will be of interest.

Photo 7.1 Drainage basin along US Highway 40, Berthoud Pass

The analysis of the peak rate of runoff, volume of runoff, and time distribution of flow is fundamental to the design of drainage facilities. Errors in estimates of these will result in a structure that is either undersized and causes more drainage problems, or oversized and costs more than necessary. The relationship between the amount of precipitation on a drainage basin and the volume of runoff from the basin is complex.

This chapter will discuss basic hydrologic concepts and provide recommendations for design frequency on CDOT projects. Hydrologic methods are also discussed and referenced, but original publications should be utilized to ensure correct application of computational procedures.

Photo 7.2 Forest fires alter the runoff patterns and volumes in watersheds

7.2 DEFINITION OF CONCEPTS

7.2.1 Overview

The following are discussions of concepts which are important in hydrologic analysis. These concepts will be used throughout this chapter.

Antecedent Moisture Conditions - A qualitative estimate of moisture in soil and plants at the beginning of a storm. These conditions affect the volume of runoff generated by a particular storm event. However, they affect the peak discharge only in the lower range of flood magnitudes, usually below the approximate 15-year event threshold. As storm magnitudes increase, the influence of antecedent moisture rapidly decreases because the soils become saturated.

Depression Storage - The natural depressions within a watershed that store runoff. Generally, after the depression storage is filled, runoff will commence.

Frequency - The number of times a flood of a given magnitude can be expected to occur on average over a long period of time. Frequency analysis is the estimation of peak discharges for various recurrence intervals. Another way to express frequency uses probability to characterize flood flow with a probability of being equaled or exceeded in any year. The exceedance probability is one divided by the return interval, expressed as a percent.

Hydraulic Roughness - A composite of physical characteristics which influence flow of water across a surface, whether natural or channelized. It affects both the time response of a watershed and drainage channel, as well as the channel-storage characteristics.

Photo 7.3 Debris flows interrupt the traffic and cause extensive damage

Hydrograph - A graph of the time distribution of runoff from a watershed.

Hyetographs - A graph of the time distribution of rainfall at a point.

Infiltration - The complex process of runoff penetrating the ground surface and flowing through the upper soil layer. An infiltration curve is a graph of the time distribution of this process.

Interception - Storage of rainfall on foliage and other intercepting surfaces during a rainfall event is called interception storage.

Lag Time - The time from the centroid of the excess rainfall to the peak of the hydrograph.

Peak Discharge - The maximum instantaneous rate of water passing a given point, during or after a rainfall event or snowmelt.

Rainfall Excess - Water available as runoff after interception, depression storage, and infiltration have taken place.

Stage - The elevation of the water surface above an elevation datum.

Time of Concentration - The time it takes a drop of water falling on the hydraulically most-remote point in the watershed to travel through the watershed to a design point.

Unit Hydrograph - The direct-runoff hydrograph resulting from a rainfall event which has a specific temporal and spatial distribution, lasts for a specific duration, and has unit volume (or results from a unit depth of rainfall). The ordinates of the unit hydrograph are such that the volume of direct runoff represented by the area under the hydrograph is equal to one inch of runoff from the drainage area. When a unit hydrograph is shown with units of ft^3/s, it is assumed that the ordinates are cubic feet per second, per inch of direct runoff.

For a more-complete discussion of these concepts and others related to hydrologic analysis, the reader is referred to the Federal Highway Administration (FHWA) Hydraulic Design Series No. 2 (HDS-2), *Highway Hydrology*.

Photo 7.4 Vegetation and land use significantly affect watershed hydrology

7.3 GENERAL CONSIDERATIONS

7.3.1 Factors Affecting Floods

In the hydrologic analysis for a drainage structure, it must be recognized that there are many factors that affect floods. Factors which need to be recognized and considered on a site-by-site basis are:

- Drainage-basin characteristics, including: size, shape, orientation, slope, length, land use, vegetation, geology, soil type, surface infiltration, watershed development, elevation, antecedent moisture condition, and storage potential (e.g., overbank, ponds, wetlands, reservoirs, and channel);
- Stream-channel characteristics, including: geometry and configuration, slope, roughness, natural and artificial controls, and channel modification;
- Floodplain characteristics, including vegetal cover and channel storage; and
- Meteorological characteristics, including: precipitation amounts and type (rain, snow, hail, or combinations), storm-cell size and distribution characteristics, storm direction, orographic factors, and time-rate of precipitation (hyetograph).

7.3.2 Sources of Information

The types and sources of information available for hydrologic analysis will vary from site to site. The designer is responsible for determining what information is available and applicable to a particular analysis. A comprehensive list of data sources is included in Chapter 6 - Data Collection.

7.3.3 Site Data

Hydrologic considerations can influence the selection of a highway corridor and the alternative routes within the corridor. Good hydrological practice should undertake studies and investigations, including consideration of the environmental and ecological impact of the project. Sensitive locations may require special studies and investigations. The magnitude and complexity of these studies should be commensurate with the importance and magnitude of the project and the problems encountered. Typical information to be included in surveys or studies includes topographic maps, aerial photographs, precipitation records, streamflow records, historical high-water elevations, historical flood discharges, and locations of hydraulic features (e.g., reservoirs, water-resource projects, designated or regulatory floodplain areas).

7.3.4 Flood History

All hydrologic analyses should consider the flood history of the area and the effect of these historical floods on existing and proposed structures.

7.3.5 Design Frequency

Since it is not economically feasible to design a structure for the maximum runoff a watershed can produce, a design frequency must be established as a basis for design. The frequency with which a given flood can be expected to occur is the reciprocal of the probability that the flood will be equaled or exceeded in a given year. If a flood has a 20% chance of being equaled or exceeded each year, over a long period of time the flood will be equaled or exceeded on an average of once every five years. This is called the return period or recurrence interval (RI). Thus, the probability equals 100/RI.

The designer should note that the 5-year flood will not necessarily be equaled or exceeded every five years. There is a 20% chance that the flood will be equaled or exceeded in any year. Therefore, the 5-year flood could conceivably occur in several consecutive years. Mathematically, the probability of non-occurrence is:

$$P_n = (1 - 1/f)^n$$

where f = year flood; and n = return period.

The probability of occurrence is:

$$P = 1 - P_n = 1 - (1 - 1/f)^n$$

For example, the chance of a 50-year flood, f, or greater event occurring in any 10-year period, n, is:

$$P = 1 - (1 - 1/50)^{10} = 0.18$$

This is an 18% chance of occurrence and an 82% chance of non-occurrence. This equation can be applied to floods with any return period.

It is standard practice to evaluate the 500-year flood in bridge-scour analysis. The 500-year flood has a 9.5% chance of occurring in a 50-year period, and an 18% chance of occurring in a 100-year period, the typical range for design life of a bridge structure

Table 7.1 Flood Probabilities

Flood Frequency *f*	Percent probability that a flood of frequency *f* or larger will occur at least once during the period of *n* years			
	1 year	**10 years**	**25 years**	**50 years**
2 years	50%	99%	99%	99%
10 years	10%	64%	93%	99%
25 years	4%	34%	64%	87%
50 years	2%	18%	40%	64%
100 years	1%	10%	22%	40%

Table 7.1 presents the flood probabilities for floods of different return periods. The values in the second column of Table 7.1 are often used to define the probability of flood occurrence, e.g., a 100-year flood is also defined as a 1% flood.

A design frequency should be selected commensurate with the facility's cost, amount of traffic, potential flood hazard to property, expected level of service, political considerations, and budgetary constraints, as well as the magnitude and risk associated with damages from larger flood events. For long highway routes with no practical detour, and where many sites are subject to independent flood events, it may be necessary to increase the design frequency at each site to avoid frequent route interruptions from floods. In selecting a design frequency, potential upstream land use should be considered which could reasonably occur over the anticipated life of the drainage facility.

Detailed evaluation of the above factors for every site to select a design frequency is generally time-consuming and tedious. The time required may not be justified on every project, and suggested standard design frequencies for various types of roads, terrain, and flood magnitudes are listed in Table 7.2. The frequencies in this table shall be used unless site conditions warrant an economic analysis to determine a different frequency. However, do not use less than a 50-year flood frequency for drainage design for through-lanes on interstate highways.

Storm-drain systems in urban areas have two separate drainage systems. One system is the minor system to handle frequently recurring storms. The minor system consists of underground piping, natural waterways, and required appurtenances to protect against average storms. The second system is the major system to handle the large, infrequent flows. The major system includes street flow and other overflow provisions to pass infrequent, large flows and protect against excessive property damage and ponding depth.

Where the standards of another agency, such as a city, exceed the values given in Table 7.2, the design must meet the higher standards unless they are demonstrably inappropriate. Appropriate city and county drainage criteria should be used on off-system projects unless higher standards are required.

Many bridges and culverts are rehabilitated before they are structurally deficient. It is possible that some of these existing structures do not meet current design criteria. All drainage structures proposed for rehabilitation should be evaluated to determine design frequency under current design criteria, and any hazards related to undersized structures. If a structure is undersized, the engineer should consider the relative risk and cost associated with rehabilitation or replacement of the drainage structure, and to determine the most appropriate action.

Table 7.2 Suggested Design Frequencies

Drainage Type	Frequency
Cross Drainage	
Multilane Roads-including interstate [a]	
Urban	100-yr
Rural	50-yr
Temporary Culverts	10-yr (monthly series)
Two-Lane Roads	
Urban	100-yr
Temporary culvert (Urban)**	10-yr (monthly series)
Rural	
$Q_{50} \geq 4000$ cfs	50-yr
$Q_{50} < 4000$ cfs	25-yr
Temporary Culverts (Rural)**	5-yr (monthly series)
Culvert Outlet Scour Protection	10-yr
Pedestrian Walkways and Bikeways	2-yr to 5-yr
Bridge Foundation Scour	100-yr and 500-yr
Parallel Drainage	
Roadway Overtopping and Revetment	Same as for cross drainage
Side Drains*	*2-yr to 5-yr
Storm Drains	
Major System	100-yr
Minor System	2-yr to 5-yr
Bridge Deck Drainage	10-yr

[a] Where no embankment overflow relief is available, drainage structures should be designed for at least the 100-yr event.

* Side drains must not cause water to flow onto the highway at a greater probability than applies to cross drainage.

** For additional information refer to *Detour Drainage Structure Design Procedure*, CDOT Research Report CDOT-DTD-R-105.095, Molinas et al., 2005.

7.3.6 Review Frequency

After sizing a drainage facility using the peak flow for the design frequency, it is necessary to evaluate the proposed facility with a review flood, or checkflood. This is done to ensure that no unexpected flood hazards are inherent in the proposed facility. The checkflood should, at a minimum, be the 100-yr (base flood) event. Where roadway or property inundation and associated damage is judged to be severe, a higher design frequency should be considered. A superflood or superstorm may be used to evaluate sites that have large potential risks or substantial initial costs. The design discharge used in an area that has a FEMA-mapped floodplain must be the 100-yr discharge.

7.3.7 500-Year Multipliers

The following multipliers can be used in estimating the Q_{500} for bridge-scour analysis:

Table 7.3 The 500-Year Flow Multipliers

Region	**Ratio** Q_{500}/Q_{100}
Mountain	1.2
Rio Grande	1.4
Southwest	1.4
Northwest	1.2
Plains	2.0

The regional boundaries in Table 7.3 are described in the *Technical Manual No. 1*, and *Techniques for Estimating Regional Flood Characteristics of Small Rural Watersheds in the Plains Region of Eastern Colorado*.

If FEMA, or another agency, has a more-detailed hydrologic study, the 500-year flood from that study must be used.

7.3.8 Rainfall vs. Flood Frequency

Drainage structures are designed based on a selected flood frequency. However, certain hydrologic procedures use rainfall and rainfall frequency as the basic input. It is commonly assumed that the 10-year rainfall will produce the 10-year flood. Depending on antecedent soil-moisture conditions and other hydrologic parameters this may or may not be true.

7.3.9 Precipitation

Colorado receives its precipitation as snow and rain. The lower elevations receive precipitation more in the form of rainfall, and snow is the common form of precipitation in the higher, colder mountainous regions.

The mountains greatly influence weather and complicate precipitation patterns. Moisture-laden air is cooled as it rises up the windward slope of a mountain, sometimes activating intense storms. Radar echoes have shown an unusually large rainstorm cell can be as much as 50 square miles in area.

Rainfall data is available for all regions in Colorado. From this data, rainfall intensity-duration curves can be developed for commonly used design frequencies. The methods used for the development of these curves are taken from the NOAA's *Atlas 14 Volume 8 Version 2.0*, and Urban Drainage and the Flood Control District of Denver (UDFCD) *Urban Storm Drainage Criteria Manual*.

7.3.10 Discharge Determination

Estimating peak discharges for various recurrence intervals is one of the most common engineering challenges faced by designers of drainage facilities. The problem can be divided into two general categories:

- Gaged sites - the site is at or near a gaging station, and the streamflow record is of sufficient duration to allow statistical estimates of peak discharges.
- Ungaged sites - the site is not near a gaging station, and no streamflow record is available.

The following section will address hydrologic procedures that can be used for both categories.

7.4 HYDROLOGIC PROCEDURE SELECTION

7.4.1 Overview

The hydrologic procedures provided in this chapter are common and routinely used. All of the procedures can be accomplished with software (see Section 7.8 - Software for Conducting Hydrologic Analyses). A summary of procedures for estimating peak discharges for various recurrence intervals is provided below for both gaged and ungaged sites. For many design situations, a complete hydrograph is needed. A summary of hydrograph procedures is provided in Section 7.5 - Hydrologic Methods.

The following list provides guidance for selection of appropriate hydrologic-analysis methods. In general, results from using several methods (at least three) should be compared, not averaged. The discharge that best reflects local-project conditions, with the reasons documented, should be used. When choosing hydrologic-analysis methods, consider:

- The Rational and Modified Rational Methods are used for routine urban designs for drainage areas under 200 acres.
- Regional-regression equations are range-specific in regression-analysis study, and have other limitations unless there is streamgauge data. Historical evidence may suggest other alternatives. Regression equation confidence limits can be used to resolve significant differences between other methods.
- Flow-distribution statistical methods (e.g., log-Pearson Type III analyses) are desirable for designs of drainage basins at or near streamflow gaging stations, provided there are at least 10 years of continuous or synthesized records.
- Colorado hydrographs are desirable to use when available (i.e. Colorado Urban Hydrograph Procedure). As an alternative, NRCS and other unit-hydrograph methods may be used.
- In a 100-year regulatory floodplain, consider the discharges and methods specified in the FEMA flood-insurance study.
- Steady (peak flow) and unsteady (hydrograph) methods exist. Selection of the peak flow versus hydrograph method typically will be based on watershed size, type of hydraulic structure, and availability of data.

7.4.2 Gaged Sites

A gaged site is a design site located at or near a gaging station where the streamflow record is of sufficient length to be used in estimating peak discharges. A complete record is defined as one having at least 25 years of continuous or synthesized data. This is relatively rare, and records as short as 10 years have been successfully used.

Procedures for analysis of streamgage data are provided in Section 7.5. Where at least 10 years of continuous or synthesized stream gage data is available, the log-Pearson Type III flood-frequency distribution can be used. It is a reliable method for estimating flood-frequency relationships where no significant changes in the watershed have occurred or are anticipated. Data can be obtained from the USGS webpage or the local USGS office. The USGS PeakFQ or USACE HEC-SSP software are commonly used for this method, see Section 7.8 - Software for Conducting Hydrologic Analyses.

7.4.3 Ungaged Sites

An ungaged site is a design location that is not near a gaging station, and no streamflow record is available. Methods for determining peak flow or runoff at ungauged sites include use of regression equations, the Rational Method, and the NRCS Graphical Peak Discharge Method.

7.4.4 Peak-Flow Rates or Hydrographs

A consideration of peak-runoff rates for design conditions is generally adequate for conveyance systems such as storm drains or open channels. However, if the design must include flood routing, a hydrograph is required. Although hydrograph development (which is more complex than estimating peak-runoff rates) is often accomplished using computer programs, some methods are adaptable to desktop procedures.

7.4.5 Time of Concentration

The time of concentration, T_c, is defined as the time it takes a drop of rain falling on the hydraulically most-remote point in the watershed to travel through the watershed to the design point. It is an important parameter and represents the moment when the entire drainage basin begins to contribute runoff to the design point. The time of concentration usually has two components. The first component is the initial time, T_i, which is the time runoff is sheet flowing. The second component, the travel time, T_t, is the time runoff is in a channel.

$$T_c = T_i + T_t$$

For overland flow in a small basin:

$$T_i = \frac{1.8\,(1.1 - C)\,D^{0.5}}{S^{0.33}}$$

where: T_i is in minutes; C = the runoff coefficient, as defined in the rational equation; D = the distance of flow path in feet (500-ft maximum for non-urban areas, 300-ft maximum for urban areas); and, S = the average slope of basin in percent (see Figure 7.1).

For channel flow:

$$T_t = (11.9\,L^3/H)^{0.385}$$

where: T_t is in hours; L = the distance of flow path in miles; and, H = the elevation difference in feet from beginning of defined channel flow to the site.

When a channel velocity is known:

$$T_t = L\,/\,(60\,V)$$

where: T_t is in minutes; V = the channel velocity in feet per second; and, L = distance in feet (see Figure 7-2).

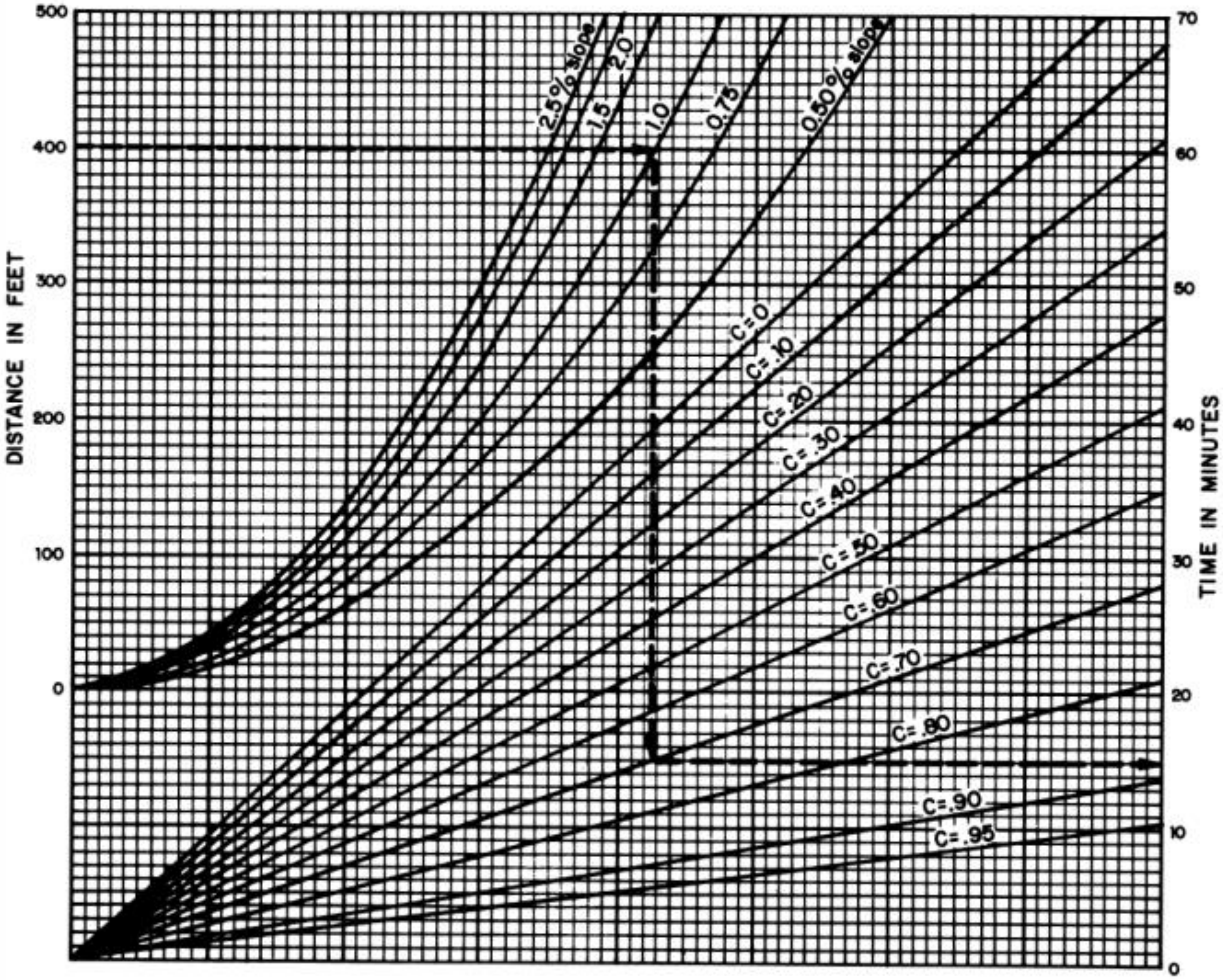

Figure 7.1 Time of Concentration for Overland Flow

In urban watersheds, the time of concentration at the first design point (including both channel and overland flow), must not exceed the following:

$$T_c = (L / 180) + 10$$

where: T_c = time of concentration, in minutes, at the first design point; and L = basin length in feet. The minimum T_c is 5 minutes in urban areas, and 10 minutes in rural areas.

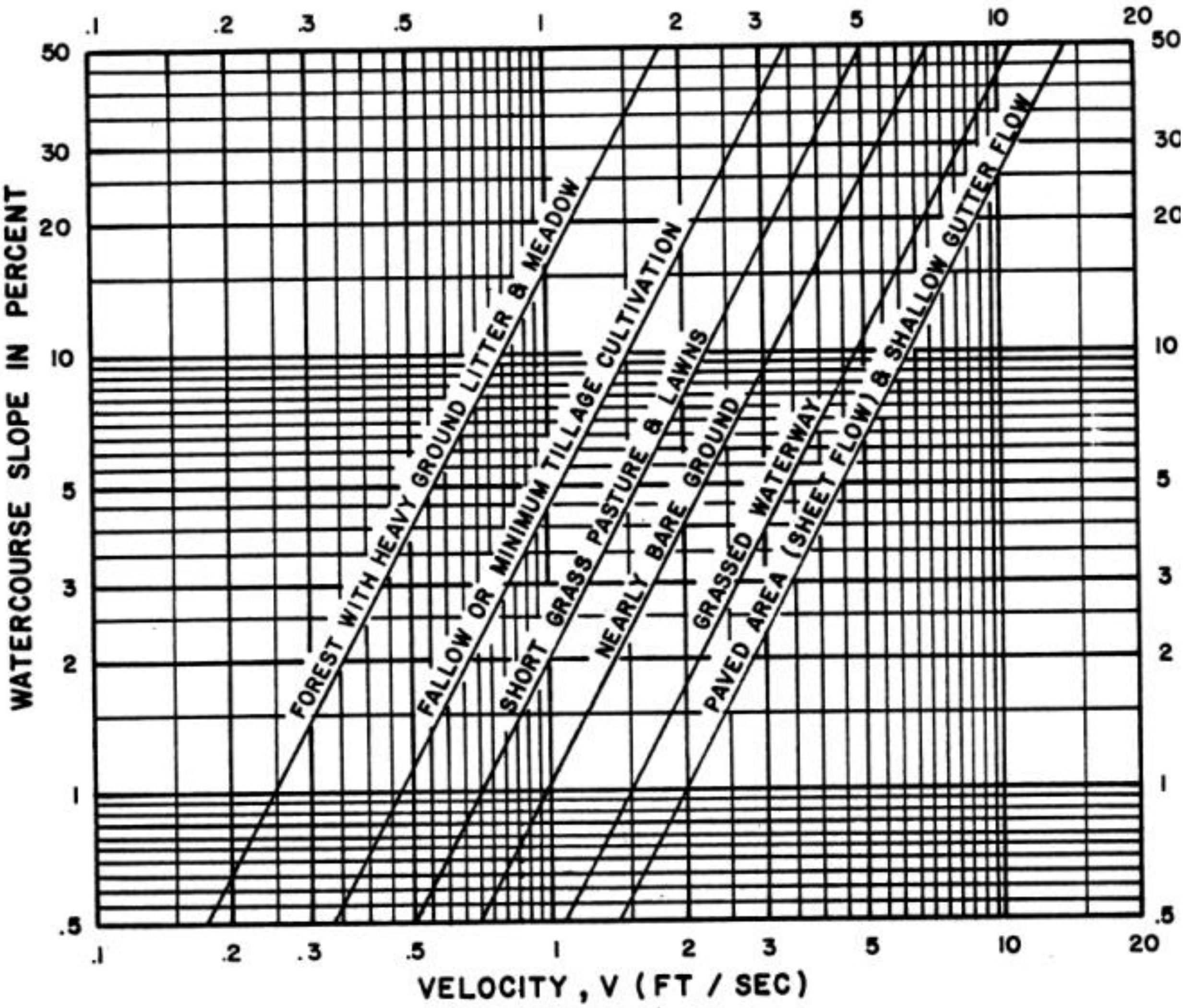

Figure 7.2 Velocities for Estimation of Time of Concentration

7.5 HYDROLOGIC METHODS

7.5.1 Hydrologic Peak Prediction and Hydrograph Procedures

Many hydrologic methods are available to predict peak discharges. Each method has a range of application, and limitations which the engineer should clearly understand prior to use. Basin size, hydrologic and geographic region, dominant precipitation type, elevation, and level of development are all important factors. The engineer must ensure that the selected hydrologic method is appropriate for the basin conditions, and that sufficient data is available to perform the required calculations. If possible, the method should be calibrated to local conditions and flood history, as described in Section 7.6. Several methods are appropriate for predicting peak-flood rates and volumes at most sites. Comparison of hydrologic prediction methods with recurrence interval curves should be performed in selection of peak-flow rates for design.

The following methods and sources can be used to determine peak-flood magnitudes for design of CDOT drainage structures.

7.5.2 Flood Insurance Studies

The 100-year discharges specified in the FEMA flood insurance study must be used to analyze impacts of a proposed crossing on a regulatory floodway. However, if these discharges are deemed outdated, the discharges based on current methods may be used, subject to receipt of necessary regulatory approvals.

7.5.3 Statistical Analysis of Streamgage Data

Flow-distribution statistical methods are desirable for designs of project sites at or near streamflow gaging stations, provided that there are at least 10 years of continuous or synthesized records. Estimates should be limited to twice the years of record (e.g., 25 years of data are needed for 50-year return-frequency discharge estimate).

The U.S. Geological Survey publishes annual streamgage data. This can be obtained from the USGS webpage or local USGS office. The method used for determining peak discharges is usually a Log-Pearson Type III distribution (see Water Resources Council's Bulletin 17B and 17C). A Log-Normal distribution or Gumbel Extreme Value distribution can also be used.

7.5.4 Regression Equations

Peak flow can be calculated using regression equations developed for specific geographic regions. The equations are in the form of a log-log formula, where the dependent variable is peak flow for a given frequency, and the independent variables may include drainage area, slope, channel geometry, and other meteorological, physical or site-specific data. The USGS has published regression equations for specific geographic regions of Colorado. Publications presenting regression equations include:

- *USGS Regional Regression Equations for Estimation of Natural Streamflow in Colorado*, developed by USGS in cooperation with the Colorado Water Conservation Board and CDOT in 2009. These equations define the statistical relationship between streamflows and basin's climatic characteristics (drainage area, mean-watershed elevation, mean-watershed slope, percentage of drainage area above 7,500 feet of elevation, mean-annual precipitation, and 6-hour, 100-year precipitation). The USGS StreamStats website can be used to compute peak flow using USGS Regional Regression Equations. For a discussion on the StreamStats program see Section 7.8 - Software for Conducting Hydrologic Analyses.
- *USGS Water Supply Papers No. 1680-1683* - Developed by the USGS, these are based on gaging-station records which have been regionalized to apply to ungaged basins.
- *Paleohydrology*, developed specifically for the foothills region of the plains, below elevations of 8,000 feet. Information from the 1976 Big Thompson flood was used to generate regression equations.
- *Channel Geometry*. This method uses the active-channel width, stream type, and terrain to predict discharge. The channel-geometry method is most accurate when applied to perennial streams with stable banks. Field procedures and regression equations are given. See USGS, "Streamflow Characteristics Related to Channel Geometry of Streams in Western United States," Water Supply Paper 2193.

7.5.5 Rational and UDFCD Modified Rational Methods

These empirical procedures provide peak-runoff rates for small urban and rural watersheds less than 200 acres but are best suited to urban drainage basins. In the Rational method, rainfall intensity is a necessary input. The method assumes constant rainfall intensity across the entire basin and that the rainfall duration equals the time of concentration.

$$Q = C\, i\, A$$

Where: Q = Peak runoff in cubic feet per second corresponding to the rainfall frequency; C = Runoff coefficient of the area; i = Rainfall intensity in inches per hour for a duration equal to the time of concentration; A = Area of contributing watershed in acres. Table 7.4 provides recommended runoff coefficients for use in the rational equation according to FHWA's HDS-2 (2002) and AASHTO Drainage Manual (2014). A more detailed derivation of runoff coefficients based on the soil category and the percent imperviousness can be found in the Urban Storm Drainage Criteria Manual, (UDFCD, 2016). Tables 7.5 and 7.6 present runoff coefficient for UDFCD's modified rational method for various soil types and return frequencies. According to UDFCD methodology, in computing the runoff coefficient (C), first imperviousness values corresponding to various land use types are determined from Table 7.5. Next, using the equations provided in Table 7.6 runoff coefficients corresponding to various soil types are computed for various return frequency periods.

The use of the rational method for hydrograph generation is not recommended because it underestimates the volume of runoff. The volume under the hydrograph should equal the amount of excess rainfall. A more detailed explanation of the Rational Method and an example on its use are provided in the AASHTO's, Drainage Manual, Chapter 9 (2014) and in FHWA' HDS-2 (2002), *Highway Hydrology.*

7.5.6 Natural Resources Conservation Service Technical Release No. 55

This method was developed by the Natural Resources Conservation Service (NRCS), formerly Soil Conservation Service, for small urban and rural watersheds (watersheds areas of 25 square miles of less, or with 24-hour or shorter times of concentration). Drainage area, rainfall characteristics, land use, and the NRCS basin soil types and conditions are the required inputs. This method tends to overpredict frequently occurring events and under-predict rare events.

7.5.7 Additional Hydrograph Methods

Colorado Urban Hydrograph Procedure – This method was developed by UDFCD for urban basins with areas greater than 90 acres. This method can be used for peak flows and hydrographs. Snyder's Unit Hydrograph method is the basis for this procedure. The equations, coefficients and procedures are available in Volume 1 of the UDFCD *Urban Storm Drainage Criteria Manual (2016).*

Snyder's Unit Hydrograph - This method, developed in 1938, has been used extensively by the Corps of Engineers, and provides a means of generating a synthetic-unit hydrograph. Amount of rainfall is a necessary input. Further explanation and examples are presented in FHWA HDS-2, *Highway Hydrology* (2002).

SCS Synthetic Unit Hydrograph - The Soil Conservation Service has developed a synthetic-unit hydrograph procedure widely used for developing rural and urban hydrographs. The unit hydrograph used by the NRCS method is based upon analysis of a large number of natural-unit hydrographs from a broad cross section of geographic locations and hydrologic regions. Amount of rainfall is a necessary input. Further explanation and examples are presented FHWA HDS-2, *Highway Hydrology (*2002).

Many of these analysis methods can be performed with software, see Section 7.8 – Software.

Table 7.4 Runoff Coefficients for the Rational Equation (AASHTO, 2014)

Type of Drainage Area	Runoff Coefficient
Business:	
Downtown area	0.70-0.95
Neighborhood areas	0.50-0.70
Residential:	
Single-family areas	0.30-0.50
Multi-units, detached	0.40-0.60
Multi-units, attached	0.60-0.75
Suburban	0.25-0.40
Apartment dwelling areas	0.50-0.70
Industrial:	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.40
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30
Lawns:	
Sandy soil, flat, < 2%	0.05-0.10
Sandy soil, average, 2 to 7%	0.10-0.15
Sandy soil, steep, > 7%	0.15-0.20
Heavy soil, flat, < 2%	0.13-0.17
Heavy soil, average 2 to 7%	0.18-0.22
Heavy soil, steep, > 7%	0.25-0.35
Streets:	
Asphalt	0.70-0.95
Concrete	0.80-0.95
Brick	0.70-0.85
Drives and walks	0.75-0.85
Roofs	0.75-0.95

Table 7.5 Percent imperviousness for computing Runoff Coefficients in Rational Method

Land Use or Surface Characteristics	Percentage Imperviousness (%)
Business:	
Downtown Areas	95
Suburban Areas	75
Residential:	
Single-family	
2.5 acres or larger	12
0.75 – 2.5 acres	20
0.25 – 0.75 acres	30
0.25 acres or less	45
Apartments	75
Industrial:	
Light areas	80
Heavy areas	90
Parks, cemeteries	10
Playgrounds	25
Schools	55
Railroad yard areas	50
Undeveloped Areas:	
Historic flow analysis	2
Greenbelts, agricultural	2
Off-site flow analysis (when land use not defined)	45
Streets:	
Paved	100
Gravel (packed)	40
Drive and walks	90
Roofs	90
Lawns, sandy soil	2
Lawns, clayey soil	2

Table 7.6 Runoff Coefficient equations based on NRCS soil groups and storm return period (UDFCD, 2016)

NRCS Soil Group	Storm Return Period					
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
A	$C_A = 0.89i$	$C_A = 0.93i$	$C_A = 0.94i$	$C_A = 0.944i$	$C_A = 0.95i$	$C_A = 0.81i + 0.154$
B	$C_B = 0.89i$	$C_B = 0.93i$	$C_B = 0.81i + 0.125$	$C_B = 0.70i + 0.23$	$C_B = 0.59i + 0.364$	$C_B = 0.49i + 0.454$
C/D	$C_{C/D} = 0.89i$	$C_{C/D} = 0.87i + 0.052$	$C_{C/D} = 0.74i + 0.2$	$C_{C/D} = 0.64i + 0.31$	$C_{C/D} = 0.54i + 0.418$	$C_{C/D} = 0.45i + 0.508$

7.6 CALIBRATION

7.6.1 Definition

Calibration is a process of varying the parameters, coefficients, or recurrence-interval curve of a hydrologic method so that it estimates peak discharges and hydrographs consistent with local rainfall, basin characteristics, streamflow data and flood history.

Figure 7.3 is an illustration of a hydrograph resulting from flow data compared to hydrographs resulting from using a non-calibrated and a calibrated hydrologic procedure. It can be seen that the calibrated hydrograph, although not exactly duplicating the hydrograph from streamflow data, is a much better representation of the streamflow hydrograph than the non-calibrated hydrograph.

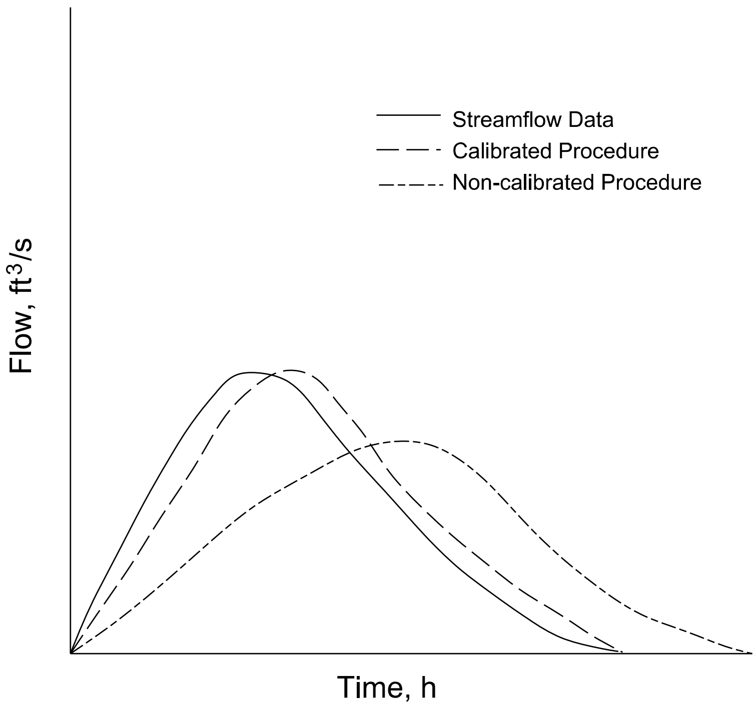

Figure 7.3 Calibrated Hydrograph

The calibration process can vary depending on the data or information available for a local area. This should only be undertaken by personnel qualified in hydrologic procedures and design.

If streamflow data is available for an area, the hydrologic procedures can be calibrated to this data. The process would involve generating peak discharges and hydrographs for different input conditions (e.g., slope, area, antecedent soil-moisture conditions) and comparing these results to the gaged data. Changes in the model would then be made to improve the estimated values when compared to the measured values. After changing the variables or parameters in the hydrologic procedure, the results should be checked against another similar gaged stream, or another portion of the streamflow data that was not used for calibration.

If a local agency has developed procedures or equations for an area based on streamflow data, general hydrologic procedures can be calibrated to these local procedures. In this way, the general hydrologic procedures can be used for a greater range of conditions (e.g., land uses, size, or slope).

If reasonable values do not produce reasonable results, then the model should be questioned and its use carefully considered (e.g., having to use terrain variables that are obviously dissimilar to the geographic area to calibrate to measured discharges or hydrographs).

7.6.2 Calibration with Flood History

Flood history for highway crossings can often be obtained from CDOT Maintenance personnel. Staff Hydraulics historically had a flood-history program, in which flood-history forms were completed by CDOT Maintenance forces. Long-time local residents can also be a source of flood history. Flood history must be used with caution, as any extreme flood or a long period of below-normal runoff may unduly influence the predicted peak flow.

The information found in Section 7.3.5 can be used to determine the frequency of a given flood-history event, such as overtopping.

7.6.3 Calibration Without Flood History

Calibration done with little or no flood history is based on the physical characteristics of the basin. Sound hydrologic principles must be employed for this type of calibration. An example of this method is increasing time of concentration to account for an unusually long and narrow basin or decreasing the time of concentration for a steep basin.

7.7 RISK ANALYSIS

7.7.1 Definition

Risk is defined as the consequences associated with the probability of flooding attributable to a given structure. There is a level of risk associated with every structure.

Risk analysis is a method used to select a design which will result in the Least Total Expected Cost (LTEC) to the traveling public. Risk analysis involves analyzing losses incurred by various design options due to possible flooding. The result of the risk analysis is the annual economic risk associated with each design option.

The sum of the annual economic risk and the annual capital costs (the total construction costs multiplied by a capital-recovery factor) is the Total Expected Cost (TEC) for each design option. Comparison of TECs for all design options allows the designer to select the option with the least total expected cost.

7.7.2 Usage

Risk analysis is used when the initial costs of a conventional design appear to produce either too much risk, excessive costs for a given site, or if requested by the Region.

7.7.3 Factors

The following items must be assessed in performing a risk analysis:

- Construction costs;
- Probable property and highway damage;
- Traffic delays;
- Availability of alternate routes; and
- Intangible considerations, including loss of emergency supply and evacuation routes, legal costs, and the potential loss of life. These require a qualitative assessment.
- Other items may include environmental considerations, water quality impacts, etc.

For each design option, costs derived from this list should be annualized over the design life of the facility before comparison with other design options.

FHWA's *The Design of Encroachments on Flood Plans Using Risk Analysis,* Hydraulic Engineering Circular No. 17, provides a more-comprehensive source of information, and methods for performing a risk analysis.

7.8 SOFTWARE FOR CONDUCTING HYDROLOGIC ANALYSES

7.8.1 Gauged Watersheds

The PeakFQ program (see Table 7.7) is used to analyze a continuous series of annual peak discharges for a gauged site so that the discharge for the design frequency can be obtained. The software reads annual peaks in the WATSTORE standard format, and in the Watershed Data Management (WDM) format. Annual peak flows are available from NWISWeb. Data should be retrieved in the WATSTORE standard format, not the tab-separated format. The StreamStats website provides access to data that has already been analyzed for gauged sites.

Table 7.7 Software for Analyzing Gaged Watersheds

Software Name	Features	Source
PeakFQ	The PeakFQ program provides estimates of instantaneous annual-maximum peak flows for a range of recurrence intervals, including 1.5, 2, 2.33, 5, 10, 25, 50, 100, 200, and 500 years (annual-exceedance probabilities of 0.6667, 0.50, 0.4292 0.20, 0.10, 0.04, 0.02, 0.01, 0.005, and 0.002, respectively). The Log-Pearson Type III frequency distribution is fit to the logarithms of instantaneous annual peak flows, following Bulletin 17B guidelines of the Interagency Advisory Committee on Water Data. The parameters of the Log-Pearson Type III frequency curve are estimated by the logarithmic sample moments (e.g., mean, standard deviation, coefficient of skewness) with adjustments for low outliers, high outliers, historic peaks, and generalized skew.	USGS website
HEC-SSP	The HEC-SSP is USACE's statistical analysis program. This software allows users to perform statistical analyses of hydrologic data. The current version of HEC-SSP can perform flood flow frequency analysis based on Bulletin	USACE website

	17B (Interagency Advisory Committee on Water Data, 1982) and Bulletin 17C (England, et al., 2018), a generalized frequency analysis on not only flow data but other hydrologic data as well, a volume frequency analysis on high or low flows, a duration analysis, a coincident frequency analysis, a curve combination analysis, a balanced hydrograph analysis, a distribution fitting analysis, and a mixed population analysis.	
StreamStats	StreamStats makes published streamflow statistics for gauged sites available without the need to locate, obtain, and read the publications in which they were originally provided. Examples of streamflow statistics that can be provided by StreamStats include the 100-yr flood; the mean annual flow; and, the 7-day, 10-yr low flow. Examples of basin characteristics include the drainage area, stream slope, mean annual precipitation, and percentage of forested area. Basin characteristics are the physical factors that control delivery of water to a point on a stream. PeakFQ and data from the USGS NWISWeb must be used to make current estimates for gauged sites.	USGS website

7.8.2 Ungaged Watersheds

The primary software for estimating peak discharge for ungaged streams is the USGS National Streamflow Statistics (NSS) software (see Table 7-8). Similar software based on the National Flood Frequency (NFF) is also available in the Watershed Management System (WMS) software. If a hydrograph is needed, WMS can be used to generate a hydrograph using the HEC-HMS, TR-20 / TR-55, or a variety of other procedures. These procedures can also be used directly.

Table 7.8 Software for Analyzing Ungauged Watersheds

Software Name	Features	Source
NFF	The USGS-published peak flow regression equations for every state were compiled into the NFF software which has been last updated in 2004. The functionality of the software has been incorporated into the USGS NSS software and WMS. The NFF reference documents provide statewide data for variables that are not found in NSS.	USGS website
NSS	The NSS software developed by the USGS contains peak-flow regression equations for every state. The software can be used to: • Obtain estimates of flood frequencies for sites in rural (non-regulated) ungauged basins; • Obtain estimates of flood frequencies for sites in urbanized basins;	USGS website

	• Estimate maximum floods based on envelope curves developed by Crippen and Bue (1977); • Create hydrographs of estimated floods for sites in rural or urban basins, and manipulate the appearance of the graphs; and • Create flood-frequency curves for sites in rural or urban basins, and manipulate the appearance of the curves.	
WMS	The Watershed Modeling System (WMS) is a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics. WMS includes powerful tools to automate modeling processes, such as automated basin delineation, geometric parameter calculations, GIS overlay computations (e.g., CN, rainfall depth, roughness coefficients), cross-section extraction from terrain data, and many more. With the release of WMS 8, the software now supports hydrologic modeling with HEC-1 (HEC-HMS), TR-20, TR-55, Rational Method, NSS, MODRAT, OC Rational, and HSPF.	Aquaveo website
HEC-HMS	The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of watershed systems. It is applicable to large river-basin water supply and flood hydrology, and small urban- or natural-watershed runoff. Hydrographs produced by the program are used directly, or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future-urbanization impact, reservoir spillway design, flood-damage reduction, floodplain regulation, and systems operation. Unit hydrograph methods include Clark, Snyder, and NRCS techniques.	HEC website
WinTR-20	The Computer Program for Project Formulation Hydrology (WinTR-20) is a single-event, watershed-scale, runoff and routing model. It computes direct runoff and develops hydrographs resulting from any synthetic or natural rainstorm. Developed hydrographs are routed through stream and valley reaches as well as through reservoirs. Hydrographs are combined from tributaries with those on the main stream. Branching flow (diversion) and baseflow can also be accommodated. WinTR-20 may be used to evaluate flooding problems, alternatives for flood control (e.g., reservoirs, channel modification, diversion), and impacts of changing land use on the hydrologic response of watersheds.	NRCS website
WinTR-55 v1.00.09	WinTR-55 is a single-event, rainfall-runoff, small-watershed hydrologic model. The model generates hydrographs from both urban and agricultural areas and at selected points along the stream system. Hydrographs can	NRCS website

	be routed downstream through channels or reservoirs, or both. Multiple sub-areas can be modeled within the watershed. Use WinTR-20 for watersheds with more than 10 sub-areas, or for watersheds larger than 25 square miles.	
FHWA Hydraulic Toolbox	The FHWA Hydraulic Toolbox Program is a stand-alone suite of calculators that performs routine hydrologic and hydraulic computations. The program allows a user to perform and save hydraulic calculations in one project file, analyze multiple scenarios, and create plots and reports of these analyses. The computations can be carried out in either CU or SI units. Nine calculators are available. The calculators of interest for hydrology are Rational Method Hydrologic Analysis (HDS-2) and Detention Basin Analysis (HEC-22).	FHWA website
StreamStats	The output from StreamStats for ungauged sites appears in a pop-up web browser window. The ungauged-site reports list only the basin characteristics that are used in the NSS regression equations for the hydrologic region in which the site is located. The reports will always include at least one table for peak-flow basin characteristics, and one table for peak-flow statistics.	USGS website

The software shown in Tables 7.7 and 7.8 are updated periodically. The most recent versions of these software are recommended for use. For current versions of software and documentation, the hydraulic engineer should consult the software source.

Available user and reference manuals are listed in the references. However, many software developers provide extensive help within the software in addition to user’s manuals.

REFERENCES

1. AASHTO, *Drainage Manual*, American Association of State Highway and Transportation Officials, Washington D.C., 2014.
2. CDOT, *Roadway Design Guide*, Colorado Department of Transportation Denver, 2005.
3. CWCB, *Guidelines for Determining 100-Year Flood Flows for Approximate Floodplains in Colorado, Version 6.0,* Colorado Water Conservation Board, Denver, 2004.
4. FHWA, *Hydrology*, Federal Highway Administration, Hydraulic Engineering Circular No. 19, Washington, D.C., October 1984.
5. FHWA, *Highway Hydrology*, Federal Highway Administration, Hydraulic Design Series No. 2, Second Edition, Washington, D.C., 2002.
6. FHWA, *The Design of Encroachments on Flood Plans Using Risk Analysis*, Hydraulic Engineering Circular No. 17, U.S. Department of Transportation, Federal Highway Administration**,** April 1981.
7. NRCS (formerly SCS), *Procedures for Determining Peak Flows in Colorado*, U.S. Department of Agriculture, Soil Conservation Service, Technical Release 55, 1984.
8. NOAA, *Atlas 14, Precipitation-Frequency Atlas of the United States, Volume 8, Version 2.0, Midwestern States*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, National Weather Service, Silver Spring, MD, 2013.
9. UDFCD, *Urban Storm Drainage Criteria Manual*, Urban Drainage and Flood Control District, 2017 and 2018.
10. USGS, *Estimation of Natural Streamflow Characteristics in Western Colorado*, U.S. Geological Survey Water Resources Investigations Report 85-4086, 1985.
11. USGS, *Manual for Estimating Flood Characteristics of Natural Flow Streams in Colorado,* U.S. Geological Survey, Technical Manual No. 1, 1976.
12. USGS, *Methods for Estimating Magnitude and Frequency of Floods in the Southwestern United States*, U.S. Geological Survey, Open File Report 93-419, 1993.
13. USGS, *Regional Regression Equations for Estimation of Natural Streamflow Statistics in Colorado*, U.S. Geological Survey, USGS Scientific Investigations Report 2009-5136, 2009.
14. USGS, *Streamflow Characteristics Related to Channel Geometry of Streams in Western United States,* U.S. Geological Survey, Water Supply Paper 2193, 1982.
15. USGS, *Techniques for Estimating Regional Flood Characteristics of Small Rural Watersheds in the Plains Region of Eastern Colorado*, U.S. Geological Survey, Water Resources Investigation Report 87-4094, 1987.
16. WRC, *Guidelines for Determining Flood Flow Frequency*, Water Resources Council, Bulletin 17B, Revised September 1981.
17. WRC, *Guidelines for Determining Flood Flow Frequency,* Water Resources Council, Bulletin 17C, Revised March 2018.