Chapter 6
Runoff

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1.0 Overview

Photograph 6-1. Devastating flooding from Gregory Canyon Creek in Boulder in September 2013 emphasizes the importance of accurate flood flow projections.

The importance of accurate runoff quantification cannot be overstated. Estimates of peak rate of runoff, runoff volume, and the time distribution of flow provide the basis for all planning, design, and construction of drainage facilities. Erroneous hydrology results in infrastructure that is either undersized, oversized, or out of hydraulic balance. At the same time it is important to understand that the result of the runoff analysis is an approximation. Thus, the intent of this chapter is to provide a reasonably dependable and consistent method of approximating the characteristics of urban runoff for areas of Colorado and the United States having similar meteorology and hydrology to what is found within the Urban Drainage and Flood Control District (UDFCD) region. Five methods of hydrologic analysis are described in the Urban Storm Drainage Criteria Manual (USDCM):

1. The Rational Method,
2. The Colorado Urban Hydrograph Procedure (CUHP) for generating hydrographs from watersheds,
3. The EPA's Storm Water Management Model (SWMM), mostly for combining and routing the hydrographs generated using CUHP,
4. Use of published runoff information, and
5. Statistical analyses.

Most of this chapter focuses on the Rational Method and CUHP in combination with SWMM routing. Table 6-1 provides a summary of applicability for both methods.

The Rational Method can be used to analyze the design storm runoff from urban catchments that are not complex and that are generally 90 acres or less and when only the peak flow rate is needed (e.g., storm drain sizing). Calculations for the Rational Method can be carried out by hand or using the UD-Rational Excel workbook available at www.udfcd.org.

Since 1969, CUHP has been used extensively in this region. It has been calibrated for the UDFCD region using data collected for a variety of watershed conditions. The vast majority of major drainage systems within UDFCD are designed based upon the hydrology calculated using CUHP and a customized version of the EPA's Stormwater Management Model (SWMM), runoff block, named the Urban Drainage Stormwater Model (UDSWM). In 2005, UDFCD began using and recommending the EPA's SWMM Version 5 and upgraded the CUHP software to be compatible with that model. CUHP and SWMM should be used for larger catchments or when a hydrograph of the storm event is needed.

There have been hydrologic studies carried out for a majority of the major drainage systems within UDFCD and published flow data are available for most of these systems.

Statistical analyses may be used in certain situations outside the UDFCD boundary. The use of this approach requires the availability of acceptable, appropriate, and adequate data.

Table 6-1. Applicability of hydrologic methods

Watershed Size (acres)	Is the Rational Method Applicable?	Is CUHP Applicable?
0 to 90	Yes	Yes
90 to 160	No	Yes
160 to 3,000	No	Yes[1]
Greater than 3,000	No	Yes (subdividing into smaller catchments required)[1]

1. Subdividing into smaller subcatchments and routing the resultant hydrographs using SWMM may be needed to accurately model a catchment with areas of different soil types or percentages of imperviousness.

When modeling large watersheds, the subcatchment sizes can influence results. If heterogeneous land uses are "lumped" together into large subcatchments, the models may not accurately account for the "flashy" nature of runoff from impervious surfaces and peak rates of runoff may be underestimated. On the other hand, defining very small subcatchments can lead to complicated and unrealistic routing that can overestimate peak rates of runoff.

The quantity of stormwater runoff from an urban site is also related to site characteristics (e.g., lot size, soil type, slope, vegetation, impervious area) and stormwater measures used to control runoff from the site (e.g., site grading, disconnecting impervious areas from the drainage system, detention facilities, buffer zones, low impact development practices, and other structural and nonstructural best management practices). Implementation of Low Impact Development (LID) strategies, including measures to "minimize directly connected impervious areas" (MDCIA), reduces runoff peaks and volumes from urban areas. These practices involve site planning to minimize impacts to sensitive site features, methods to reduce the overall amount of impervious areas, and routing of runoff from impervious surfaces over permeable areas to slow runoff (increase time of concentration) and promote onsite storage and infiltration. Volume 3 of the USDCM contains additional information on LID practices.

2.0 Rational Method

For urban catchments that are not complex and are generally 90 acres or less in size, it is acceptable to use the Rational Method for design storm analysis. Most engineering offices in the United States continue to use this method originally introduced in 1889. Even though this method has frequently come under academic criticism for its simplicity, no other practical drainage design method has evolved to such a level of general acceptance by the practicing engineer. The Rational Method, properly understood and applied, can produce satisfactory results for urban storm drain design and small on-site detention design and for sizing of street inlets and storm drains.

2.1 Rational Formula

The Rational Method is based on the Rational Formula:

$$Q = CIA \qquad \text{Equation 6-1}$$

Where:

Q = the peak rate of runoff (cfs)

C = Runoff coefficient–a non-dimensional coefficient equal to the ratio of runoff volume to rainfall volume

I = average intensity of rainfall for a duration equal to the time of concentration, t_c (inches/hour)

A = tributary area (acres).

Actually, Q has a unit of inches per hour per acre (in/hour/ac); however, since this rate of acre-inches/hour differs from cubic feet per second (cfs) by less than one percent, the more common units of cfs are used. The time of concentration is defined as the time required for water to flow from the most remote point of the tributary area to the design point, and is determined for the selected flow length that represents the longest waterway through a rural watershed or the most representative flow path through the impervious portion in an urban catchment.

The general procedure for Rational Method calculations for a single catchment is as follows:

1. Delineate the catchment boundary and determine its area.
2. Define the flow path from the upper-most portion of the catchment to the design point. Divide the flow path into reaches of similar flow type (e.g., overland flow, shallow swale flow, gutter flow, etc.). Determine the length and slope of each reach.
3. Determine the time of concentration, t_c, for the selected waterway.
4. Find the rainfall intensity, I, for the design storm using the calculated t_c and the rainfall intensity-duration-frequency curve (see *Rainfall* chapter).
5. Determine the runoff coefficient, C.
6. Calculate the peak flow rate, Q, from the catchment using Equation 6-1.

2.2 Assumptions

The basic assumptions for the application of the Rational Method include:

1. The computed maximum rate of runoff to the design point is a function of the average rainfall rate during the time of concentration to that point.
2. The hydrologic losses in the catchment are homogeneous and uniform. The runoff coefficients vary with respect to type of soils, imperviousness percentage, and rainfall frequencies. These coefficients represent the average antecedent soil moisture condition.
3. The depth of rainfall used is one that occurs from the start of the storm to the time of concentration. The design rainfall depth during that period is converted to the average rainfall intensity for that period.
4. The maximum runoff rate occurs when the entire area is contributing flow. This assumption is not valid where a more intensely developed portion of the catchment with a shorter time of concentration produces a higher rate of runoff than the entire catchment with a longer time of concentration.

2.3 Limitations

The Rational Method is the simplistic approach for estimating the peak flow rate and total runoff volume from a design rainstorm in a given catchment. Under the assumption of uniform hydrologic losses, the method is limited to catchments smaller than 90 acres. Under the condition of composite soils and land uses, use an area-weighted method to derive the catchment's hydrologic parameters.

The greatest drawback to the Rational Method is that it normally provides only one point (the peak flow rate) on the runoff hydrograph. When the areas become complex and where subcatchments come together, the Rational Method will tend to overestimate the actual flow, which results in oversizing of drainage facilities. The Rational Method provides no means or methodology to generate and route hydrographs through drainage facilities. One reason the Rational Method is limited to small areas is that good design practice requires the routing of hydrographs for larger catchments to achieve an economically sound design.

Another disadvantage of the Rational Method is that with typical design procedures, one normally assumes that all of the design flow is collected at the design point and that there is no water running overland to the next design point. This is not an issue of the Rational Method but of the design procedure. Use additional analysis to account for this scenario.

2.4 Time of Concentration

One of the basic assumptions underlying the Rational Method is that runoff is linearly proportional to the average rainfall intensity during the time required for water to flow from the most remote part of the drainage area to the design point. In practice, the time of concentration is empirically estimated along the selected waterway through the catchment.

To calculate the time of concentration, first divide the waterway into overland flow length and channelized flow lengths, according to the channel characteristics. For urban areas (tributary areas of greater than 20 percent impervious), the time of concentration, t_c, consists of an initial time or overland flow time, t_i, plus the channelized flow travel time, t_t, through the storm drain, paved gutter, roadside ditch, or channel. For non-urban areas, the time of concentration consists of an overland flow time, t_i, plus the time of travel in a defined drainage path, such as a swale, channel, or stream. Estimate the channelized travel time portion, t_t, of the time of concentration from the hydraulic properties of the conveyance element. Initial or overland flow time, on the other hand, will vary with surface slope, depression storage, surface cover, antecedent rainfall, and infiltration capacity of the soil, as well as distance of surface flow. Compute the time of concentration for both urban and non-urban areas using Equation 6-2:

$$t_c = t_i + t_t \qquad \text{Equation 6-2}$$

Where:

t_c = computed time of concentration (minutes)

t_i = overland (initial) flow time (minutes)

t_t = channelized flow time (minutes).

2.4.1 Initial or Overland Flow Time

The initial or overland flow time, t_i, may be calculated using Equation 6-3:

$$t_i = \frac{0.395(1.1 - C_5)\sqrt{L_i}}{S_o^{0.33}} \qquad \text{Equation 6-3}$$

Where:

t_i = overland (initial) flow time (minutes)
C_5 = runoff coefficient for 5-year frequency (from Table 6-4)
L_i = length of overland flow (ft)
S_o = average slope along the overland flow path (ft/ft).

Equation 6-3 is adequate for distances up to 300 feet in urban areas and 500 feet in rural areas. Note that in a highly urbanized catchment, the overland flow length is typically shorter than 300 feet due to effective man-made drainage systems that collect and convey runoff.

2.4.2 Channelized Flow Time

The channelized flow time (travel time) is calculated using the hydraulic properties of the conveyance element. The channelized flow time, t_t, is estimated by dividing the length of conveyance by the velocity. The following equation, Equation 6-4 (Guo 2013), can be used to determine the flow velocity in conjunction with Table 6-2 for the conveyance factor.

$$t_t = \frac{L_t}{60K\sqrt{S_o}} = \frac{L_t}{60V_t} \qquad \text{Equation 6-4}$$

Where:

t_t = channelized flow time (travel time, min)
L_t = waterway length (ft)
S_o = waterway slope (ft/ft)
V_t = travel time velocity (ft/sec) = $K\sqrt{S_o}$
K = NRCS conveyance factor (see Table 6-2).

Table 6-2. NRCS Conveyance factors, K

Type of Land Surface	Conveyance Factor, K
Heavy meadow	2.5
Tillage/field	5
Short pasture and lawns	7
Nearly bare ground	10
Grassed waterway	15
Paved areas and shallow paved swales	20

The time of concentration, t_c, is the sum of the initial (overland) flow time, t_i, and the channelized flow time, t_t, as per Equation 6-2.

2.4.3 First Design Point Time of Concentration in Urban Catchments

Equation 6-4 was solely determined by the waterway characteristics and using a set of empirical formulas. A calibration study between the Rational Method and the Colorado Urban Hydrograph Procedure (CUHP) suggests that the time of concentration shall be the lesser of the values calculated by Equation 6-2 and Equation 6-5 (Guo and Urbonas 2013).

$$t_c = (26 - 17i) + \frac{L_t}{60(14i + 9)\sqrt{S_t}} \qquad \text{Equation 6-5}$$

Where:

t_c = minimum time of concentration for first design point when less than t_c from Equation 6-1.
L_t = length of channelized flow path (ft)
i = imperviousness (expressed as a decimal)
S_t = slope of the channelized flow path (ft/ft).

Equation 6-5 is the regional time of concentration that warrants the best agreement on peak flow predictions between the Rational Method and CUHP when the imperviousness of the tributary area is greater than 20 percent. It was developed using the UDFCD database that includes 295 sample urban catchments under 2-, 5-, 10-, 50, and 100-yr storm events (MacKenzie 2010). It suggests that both initial flow time and channelized flow velocity are directly related to the catchment’s imperviousness (Guo and MacKenzie 2013).

The first design point is defined as a node where surface runoff enters the storm drain system. For example, all inlets are “first design points” because inlets are designed to accept flow into the storm drain.

Typically, but not always, Equation 6-5 will result in a lesser time of concentration at the first design point and will govern in an urbanized watershed. For subsequent design points, add the travel time for each relevant segment downstream.

2.4.4 Minimum Time of Concentration

Use a minimum t_c value of 5 minutes for urbanized areas and a minimum t_c value of 10 minutes for areas that are not considered urban. Use minimum values even when calculations result in a lesser time of concentration.

2.4.5 Common Errors in Calculating Time of Concentration

A common mistake in urbanized areas is to assume travel velocities that are too slow. Another common error is to not check the runoff peak resulting from only part of the catchment. Sometimes a lower portion of the catchment or a highly impervious area produces a larger peak than that computed for the whole catchment. This error is most often encountered when the catchment is long or the upper portion contains grassy open land and the lower portion is more developed.

2.5 Rainfall Intensity

The calculated rainfall intensity, *I*, is the average rainfall rate in inches per hour for the period of maximum rainfall having a duration equal to the time of concentration.

After the design storm recurrence frequency has been selected, a graph should be made showing rainfall intensity versus time. The procedure for obtaining the local data and plotting such a graph is explained and illustrated in the *Rainfall* chapter of the USDCM. The UD-Rain Excel workbook can also be used for calculating the intensity. This workbook is available for download at www.udfcd.org.

Photograph 6-2. Urbanization (impervious area) increases runoff volumes, peak discharges, frequency of runoff, and receiving stream degradation.

2.5.1 Runoff Coefficient

Each part of a watershed can be considered as either pervious or impervious. The pervious part is the area where water can readily infiltrate into the ground. The impervious part is the area that does not readily allow water to infiltrate into the ground, such as areas that are paved or covered with buildings and sidewalks or compacted unvegetated soils. In urban hydrology, the percentage of pervious and impervious land is important. Urbanization increases impervious area causing rainfall-runoff relationships to change significantly. In the absence of stormwater management methods such as low impact development and green infrastructure, the total runoff volume increases, the time to the runoff peak rate decreases, and the peak runoff rate increases.

When analyzing a watershed for planning or design purposes, the probable future percent of impervious area must be estimated. A complete tabulation of recommended values of the total percent of imperviousness is provided in Table 6-3.

The runoff coefficient, *C*, represents the integrated effects of infiltration, evaporation, retention, and interception, all of which affect the volume of runoff. The determination of *C* requires judgment based on experience and understanding on the part of the engineer.

Volume-based runoff coefficients were derived to establish the optimal consistency between CUHP and the Rational Method for peak flow predictions (Guo, 2013). Using the percentage imperviousness, the equations in Table 6-4 can be used to calculate the runoff coefficients for hydrologic soil groups A, B, and C/D for various storm return periods.

Table 6-3. Recommended percentage imperviousness values

Land Use or Surface Characteristics	Percentage Imperviousness (%)
Business:	
Downtown Areas	95
Suburban Areas	75
Residential lots (lot area only)**:**	
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 6-4. Runoff coefficient equations based on NRCS soil group and storm return period

NRCS Soil Group	Storm Return Period						
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year	500-Year
A	$C_A = 0.84i^{1.302}$	$C_A = 0.86i^{1.276}$	$C_A = 0.87i^{1.232}$	$C_A = 0.88i^{1.124}$	$C_A = 0.85i+0.025$	$C_A = 0.78i+0.110$	$C_A = 0.65i+0.254$
B	$C_B = 0.84i^{1.169}$	$C_B = 0.86i^{1.088}$	$C_B = 0.81i+0.057$	$C_B = 0.63i+0.249$	$C_B = 0.56i+0.328$	$C_B = 0.47i+0.426$	$C_B = 0.37i+0.536$
C/D	$C_{C/D} = 0.83i^{1.122}$	$C_{C/D} = 0.82i+0.035$	$C_{C/D} = 0.74i+0.132$	$C_{C/D} = 0.56i+0.319$	$C_{C/D} = 0.49i+0.393$	$C_{C/D} = 0.41i+0.484$	$C_{C/D} = 0.32i+0.588$

Where:

i = % imperviousness (expressed as a decimal)

C_A = Runoff coefficient for Natural Resources Conservation Service (NRCS) HSG A soils

C_B = Runoff coefficient for NRCS HSG B soils

$C_{C/D}$ = Runoff coefficient for NRCS HSG C and D soils.

The values for various catchment imperviousness and storm return periods are presented graphically in Figures 6-1 through 6-3, and are tabulated in Table 6-5. These coefficients were developed for the Denver region to work in conjunction with the time of concentration recommendations in Section 2.4. Use of these coefficients and this procedure outside of the semi-arid climate found in the Denver region may not be valid. The UD-Rational Excel workbook performs all the needed calculations to find the runoff coefficient given the soil type and imperviousness and the reader may want to take advantage of this macro-enabled Excel workbook that is available for download from the UDFCD's website www.udfcd.org.

See Examples 7.1 and 7.2 that illustrate the Rational Method.

Table 6-5. Runoff coefficients, *c*

Total or Effective % Impervious	**NRCS Hydrologic Soil Group A**						
	2-Year	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**	**500-Year**
2%	0.01	0.01	0.01	0.01	0.04	0.13	0.27
5%	0.02	0.02	0.02	0.03	0.07	0.15	0.29
10%	0.04	0.05	0.05	0.07	0.11	0.19	0.32
15%	0.07	0.08	0.08	0.1	0.15	0.23	0.35
20%	0.1	0.11	0.12	0.14	0.2	0.27	0.38
25%	0.14	0.15	0.16	0.19	0.24	0.3	0.42
30%	0.18	0.19	0.2	0.23	0.28	0.34	0.45
35%	0.21	0.23	0.24	0.27	0.32	0.38	0.48
40%	0.25	0.27	0.28	0.32	0.37	0.42	0.51
45%	0.3	0.31	0.33	0.36	0.41	0.46	0.54
50%	0.34	0.36	0.37	0.41	0.45	0.5	0.58
55%	0.39	0.4	0.42	0.45	0.49	0.54	0.61
60%	0.43	0.45	0.47	0.5	0.54	0.58	0.64
65%	0.48	0.5	0.51	0.54	0.58	0.62	0.67
70%	0.53	0.55	0.56	0.59	0.62	0.65	0.71
75%	0.58	0.6	0.61	0.64	0.66	0.69	0.74
80%	0.63	0.65	0.66	0.69	0.71	0.73	0.77
85%	0.68	0.7	0.71	0.74	0.75	0.77	0.8
90%	0.73	0.75	0.77	0.79	0.79	0.81	0.84
95%	0.79	0.81	0.82	0.83	0.84	0.85	0.87
100%	0.84	0.86	0.87	0.88	0.88	0.89	0.9
Total or Effective % Impervious	**NRCS Hydrologic Soil Group B**						
	2-Year	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**	**500-Year**
2%	0.01	0.01	0.07	0.26	0.34	0.44	0.54
5%	0.03	0.03	0.1	0.28	0.36	0.45	0.55
10%	0.06	0.07	0.14	0.31	0.38	0.47	0.57
15%	0.09	0.11	0.18	0.34	0.41	0.5	0.59
20%	0.13	0.15	0.22	0.38	0.44	0.52	0.61
25%	0.17	0.19	0.26	0.41	0.47	0.54	0.63
30%	0.2	0.23	0.3	0.44	0.49	0.57	0.65
35%	0.24	0.27	0.34	0.47	0.52	0.59	0.66
40%	0.29	0.32	0.38	0.5	0.55	0.61	0.68
45%	0.33	0.36	0.42	0.53	0.58	0.64	0.7
50%	0.37	0.4	0.46	0.56	0.61	0.66	0.72
55%	0.42	0.45	0.5	0.6	0.63	0.68	0.74
60%	0.46	0.49	0.54	0.63	0.66	0.71	0.76
65%	0.5	0.54	0.58	0.66	0.69	0.73	0.77
70%	0.55	0.58	0.62	0.69	0.72	0.75	0.79
75%	0.6	0.63	0.66	0.72	0.75	0.78	0.81
80%	0.64	0.67	0.7	0.75	0.77	0.8	0.83
85%	0.69	0.72	0.74	0.78	0.8	0.82	0.85
90%	0.74	0.76	0.78	0.81	0.83	0.84	0.87
95%	0.79	0.81	0.82	0.85	0.86	0.87	0.88
100%	0.84	0.86	0.86	0.88	0.89	0.89	0.9

Table 6-5. Runoff coefficients, *c* (continued)

Total or Effective % Impervious	NRCS Hydrologic Soil Group C						
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year	500-Year
2%	0.01	0.05	0.15	0.33	0.40	0.49	0.59
5%	0.03	0.08	0.17	0.35	0.42	0.5	0.6
10%	0.06	0.12	0.21	0.37	0.44	0.52	0.62
15%	0.1	0.16	0.24	0.4	0.47	0.55	0.64
20%	0.14	0.2	0.28	0.43	0.49	0.57	0.65
25%	0.18	0.24	0.32	0.46	0.52	0.59	0.67
30%	0.22	0.28	0.35	0.49	0.54	0.61	0.68
35%	0.26	0.32	0.39	0.51	0.57	0.63	0.7
40%	0.3	0.36	0.43	0.54	0.59	0.65	0.71
45%	0.34	0.4	0.46	0.57	0.62	0.67	0.73
50%	0.38	0.44	0.5	0.6	0.64	0.69	0.75
55%	0.43	0.48	0.54	0.63	0.66	0.71	0.76
60%	0.47	0.52	0.57	0.65	0.69	0.73	0.78
65%	0.51	0.56	0.61	0.68	0.71	0.75	0.79
70%	0.56	0.61	0.65	0.71	0.74	0.77	0.81
75%	0.6	0.65	0.68	0.74	0.76	0.79	0.82
80%	0.65	0.69	0.72	0.77	0.79	0.81	0.84
85%	0.7	0.73	0.76	0.79	0.81	0.83	0.86
90%	0.74	0.77	0.79	0.82	0.84	0.85	0.87
95%	0.79	0.81	0.83	0.85	0.86	0.87	0.89
100%	0.83	0.85	0.87	0.88	0.89	0.89	0.9

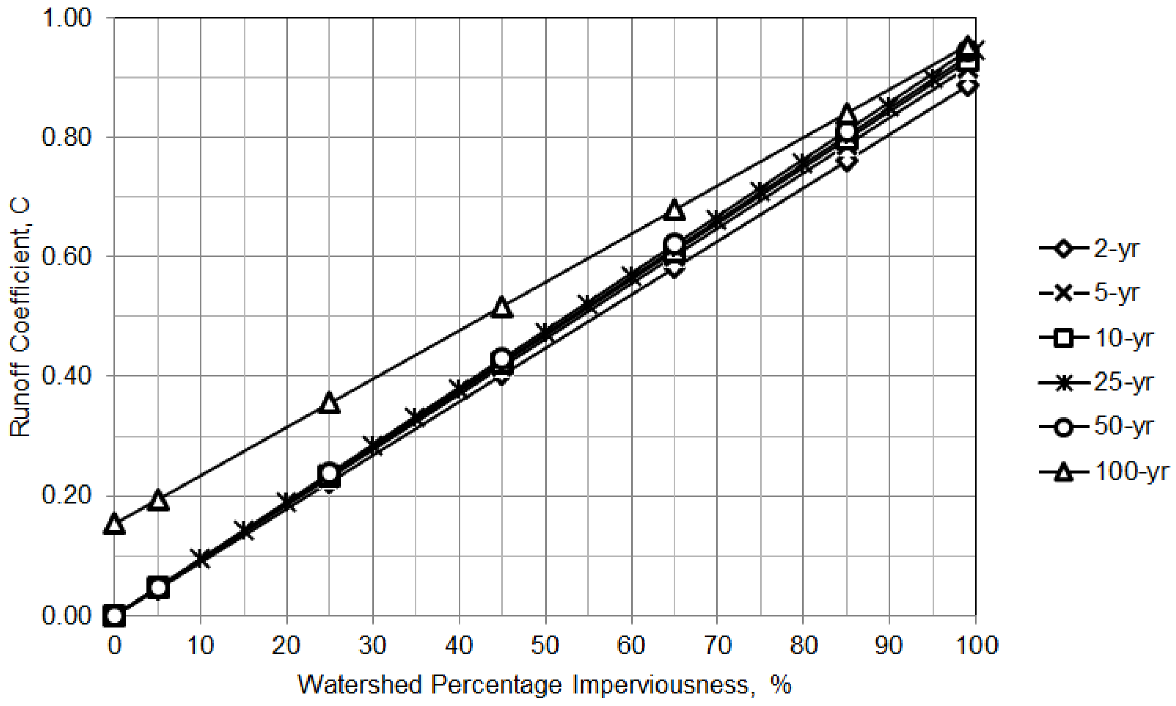


Figure 6-1. Runoff coefficient vs. watershed imperviousness NRCS HSG A

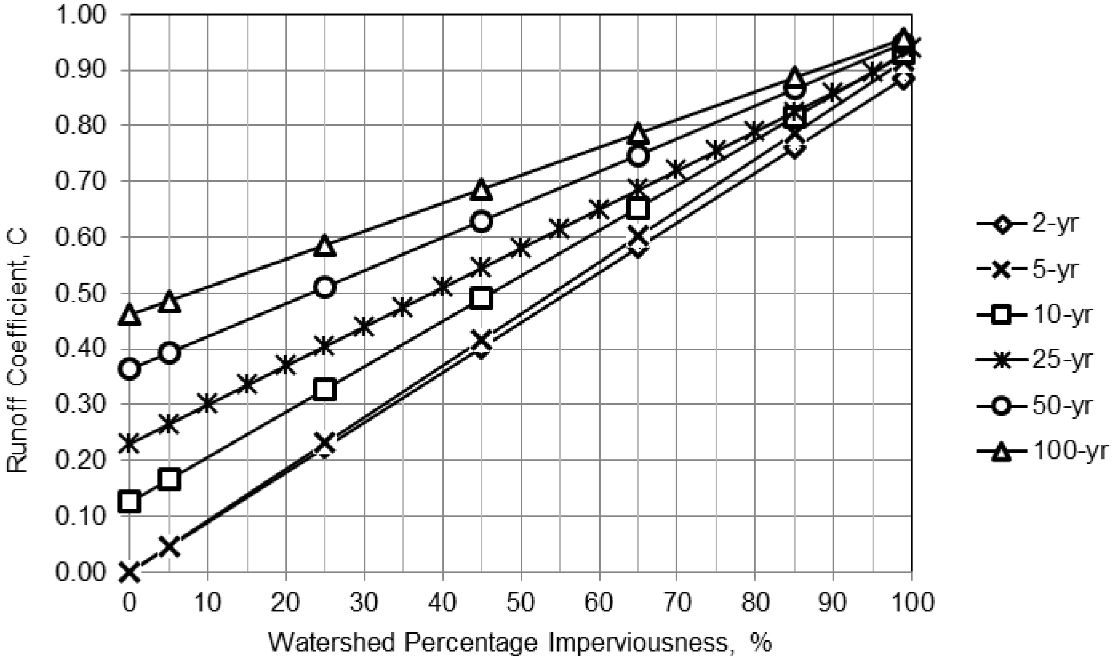


Figure 6-2. Runoff coefficient vs. watershed imperviousness NRCS HSG B

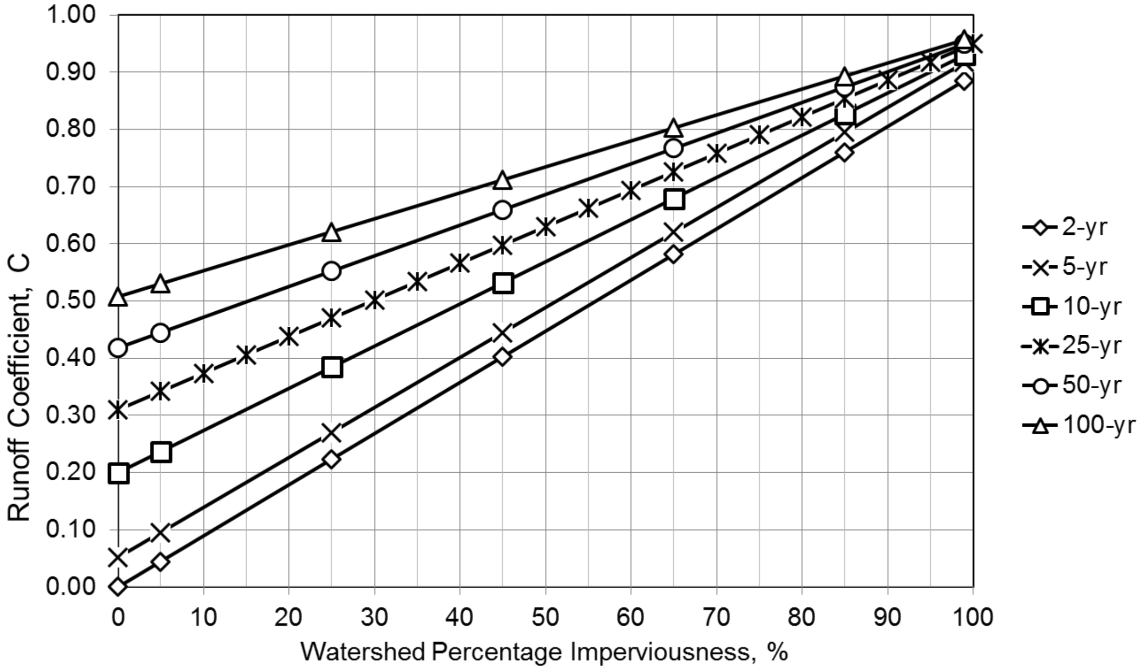


Figure 6-3. Runoff coefficient vs. watershed imperviousness NRCS HSG C and D

3.0 Colorado Urban Hydrograph Procedure

3.1 Background

The Colorado Urban Hydrograph Procedure (CUHP) is a method of hydrologic analysis based upon the unit hydrograph principle. A unit hydrograph is defined as the hydrograph of one inch of direct runoff from the tributary area resulting from a storm of a given duration. The unit hydrograph thus represents the integrated effects of factors such as tributary area, shape, street pattern, channel capacities, and street and land slopes. The basic premise of the unit hydrograph is that individual hydrographs resulting from the successive increments of excess rainfall that occur throughout a storm period will be proportional in discharge throughout their runoff period. Thus, the hydrograph of total storm discharge is obtained by summing the ordinates of the individual sub-hydrographs.

CUHP has been developed and calibrated using rainfall-runoff data collected in Colorado (mostly in the Denver/Boulder metropolitan area). This section provides a general background in the use of the computer version of CUHP to perform stormwater runoff calculations. A detailed description of the CUHP method and the assumptions and equations used, including a hand calculation example, are provided in the CUHP User Manual. The latest version of the CUHP 2005 macro-enabled Excel workbook and User Manual are available for download from www.udfcd.org.

3.2 Effective Rainfall for CUHP

Effective rainfall is that portion of precipitation during a storm event that runs off the land to streams. Those portions of precipitation that do not reach a stream are called abstractions and include interception by vegetation, evaporation, infiltration, storage in all surface depressions, and extended duration surface retention. The total design rainfall depth for use with CUHP should be obtained from the *Rainfall* chapter of the USDCM. This chapter illustrates a method for estimating the amount of rainfall that actually becomes surface runoff whenever a design rainstorm is used.

3.2.1 Pervious-Impervious Areas

As described in Section 2.5.1, the urban landscape is comprised of pervious and impervious surfaces. The degree of imperviousness is the primary variable that affects the volumes and rates of runoff calculated using CUHP. When analyzing a watershed for design purposes, the probable future percent of impervious area must first be estimated. A complete tabulation of recommended values of total percentage imperviousness is provided in Table 6-3 and Figures 6-1 through 6-3. References to impervious area and all calculations in this chapter are based on the input of total impervious areas. The pervious-impervious area relationship can be further refined for use in CUHP as follows:

- **DCIA**: Impervious area portion directly connected to the drainage system.
- **UIA:** Impervious area portion that drains onto or across pervious surfaces.
- **RPA**: The portion of pervious area receiving runoff from impervious portions.
- **SPA:** The separate pervious area portion not receiving runoff from impervious surfaces.

This further refinement is explained in more detail in the CUHP User Manual and in Chapter 3 of the USDCM Volume 3.

3.2.2 Depression Losses

Rainwater that is collected and held in small depressions and does not become part of the general surface runoff is called depression loss. Most of this water eventually infiltrates or evaporates. Depression losses also include water intercepted by trees, bushes, other vegetation, and all other surfaces. The CUHP method requires numerical values of depression loss as inputs to calculate the effective rainfall. Table 6-6 can be used as a guide in estimating the amount of depression (retention) losses to be used with CUHP.

Table 6-6. Typical depression losses for various land covers

(All values in inches for use with the CUHP.)

Land Cover	Range in Depression (Retention) Losses	Recommended
Impervious:		
Large paved areas	0.05 - 0.15	0.1
Roofs-flat	0.1 - 0.3	0.1
Roofs-sloped	0.05 - 0.1	0.05
Pervious:		
Lawn grass	0.2 - 0.5	0.35
Wooded areas and open fields	0.2 - 0.6	0.4

When an area is analyzed for depression losses, the pervious and impervious loss values for all parts of the watershed must be considered and accumulated in proportion to the percent of aerial coverage for each type of surface.

3.2.3 Infiltration

Flow of water into the soil surface is called infiltration. In urban hydrology much of the infiltration occurs on areas covered with grass. Urbanization can increase or decrease the total amount of infiltration depending on how the runoff is managed, historic use of the area and other factors.

Soil type is the most important factor in determining the infiltration rate. When the soil has a large percentage of well-graded fines, the infiltration rate is low. In some cases of extremely tight soil there may be, from a practical standpoint, essentially no infiltration. If the soil has several layers or horizons, the least permeable layer near the surface will control the maximum infiltration rate. The soil cover also plays an important role in determining the infiltration rate. Vegetation, lawn grass in particular, tends to increase infiltration by loosening the soil near the surface. Other factors affecting infiltration rates include slope of land, temperature, quality of water, age of lawn, and soil compaction. Of these, CUHP considers only the slope.

As rainfall continues, the infiltration rate decreases. When rainfall occurs on an area that has little antecedent moisture and the ground is dry, the infiltration rate can be much higher than it is with high antecedent moisture resulting from previous storms or land irrigation such as lawn watering. Although antecedent precipitation is important when calculating runoff from smaller storms in non-urbanized areas, the runoff data from urbanized watersheds indicates that antecedent precipitation has a smaller effect on runoff peaks and volumes in the urbanized portions of UDFCD.

There are many infiltration models in use by hydrologists. These models vary significantly in complexity. Because of the climatic condition in the semi-arid region and because runoff from urban watersheds is not very sensitive to infiltration refinements, the infiltration model proposed by Horton was found to provide a good balance between simplicity and reasonable physical description of the infiltration process for use in CUHP. Equation 6-6 describes Horton's infiltration model.

$$f = f_o + \left(f_i - f_o\right) e^{-at} \qquad \text{Equation 6-6}$$

Where:

f = infiltration rate at any given time t from start of rainfall (in/hr)

f_o = final infiltration rate (in/hr)

f_i = initial infiltration rate (in/hr)

e = natural logarithm base

a = decay coefficient (1/second)

t = time (seconds).

In developing Equation 6-6, Horton observed that infiltration is high early in the storm and eventually decays to a steady state constant value as the pores in the soil become saturated. The coefficients and initial and final infiltration values are site specific and depend on the soils and vegetative cover. With sufficient rainfall-runoff observations, it is possible to develop these values for a specific site.

Since 1977, UDFCD has analyzed a considerable amount of rainfall-runoff data. Based on this analysis, UDFCD recommends using the values in Table 6-7 within the UDFCD region with CUHP. The NRCS Hydrologic Soil Groups C and D occur most frequently within UDFCD; however, areas of NRCS Group A and B soils also exist. Consult NRCS soil surveys for appropriate soil classifications.

Table 6-7. Recommended Horton's equation parameters

NRCS Hydrologic Soil Group	Infiltration (inches per hour)		Decay Coefficient—a
	Initial—f_i	Final—f_o	
A	5.0	1.0	0.0007
B	4.5	0.6	0.0018
C	3.0	0.5	0.0018
D	3.0	0.5	0.0018

To calculate the maximum infiltration depths that may occur at each time increment, it is necessary to integrate Equation 6-6 and calculate the values for each time increment. Very little accuracy is lost if, instead of integrating Equation 6-6, the infiltration rate is calculated at the center of each time increment. This "central" value can then be multiplied by the unit time increment to estimate the infiltration depth. Although Table 6-7 provides recommended values for various Horton equation parameters, these recommendations are being made specifically for the urbanized or urbanizing watersheds in the Denver metropolitan area and may not be valid in different meteorological and climatic regions.

3.3 CUHP Parameter Selection

3.3.1 Rainfall

The CUHP 2005 Excel workbook requires the input of a design storm, either as a user-defined hyetograph or as a program generated hyetograph using 1-hour and 6-hour rainfall depths. The CUHP program generates a hyetograph using the 1-hour depth and the standard 2-hour temporal distribution recommended in the *Rainfall* chapter of the USDCM. In addition, the program will also generate a 6-hour storm distribution with area corrections accounted for in cases where larger watersheds are studied.

3.3.2 Catchment Description

The following catchment parameters are required for the program to generate a unit and storm hydrograph.

- **Area:** Catchment area in square miles. See Table 6-1 for catchment size limits. Typically, a 5-minute unit hydrograph is used in CUHP. However, for catchments smaller than 90 acres, using a 1-minute unit hydrograph is recommended particularly if significant differences are found between the "excess precipitation" and "runoff hydrograph" volumes listed in the summary output. For very small catchments (i.e. smaller than 10 acres), especially those with high imperviousness, the 1-minute unit hydrograph will be needed to preserve runoff volume integrity.

- **Length:** The length in miles from the downstream design point of the catchment or subcatchment along the main flow path to the furthest point on its respective catchment or subcatchment boundary. When subdividing a catchment into a series of subcatchments, the subcatchment length shall include the distance required for runoff to reach the major drainageway from the farthest point in the subcatchment.

- **Length to Centroid:** Distance in miles from the design point of the catchment or subcatchment along the stream path to its respective catchment or subcatchment centroid.

- **Slope:** The length-weighted, corrected average slope of the catchment in feet per foot.

    - There are natural processes at work that limit the time to peak of a unit hydrograph as a natural stream or vegetated channel becomes steeper. To account for this phenomenon, it is recommended that the slope used in CUHP for streams and vegetated channels be adjusted using Figure 6-4.

    - When a riprap channel is evaluated, use the measured (i.e., uncorrected) average channel invert slope.

    - In concrete-lined channels and buried conduits, the velocities can be very high. For this reason, UDFCD recommends use of the average ground slope (i.e., not flow-line slope) where concrete-lined channels and/or storm drains dominate. There is no correction factor or upper limit recommended to the slope for concrete-lined channels and buried conduits.

Where the flow-line slope varies along the channel, calculate a weighted sub-catchment slope for use with CUHP. Do this by first segmenting the major drainageway into reaches having similar longitudinal slopes. Then calculate the weighted slope using the Equation 6-7.

$$S = \left[\frac{L_1 S_1^{\ 0.24} + L_2 S_2^{\ 0.24} + ... + L_n S_n^{\ 0.24}}{L_1 + L_2 + L_3 .... L_n} \right]^{4.17} \qquad \text{Equation 6-7}$$

Where:

S = weighted basin waterway slopes in ft/ft

$S_1, S_2, \ldots S_n$ = slopes of individual reaches in ft/ft (after adjustments using Figure 6-4)

$L_1, L_2, \ldots L_n$ = lengths of corresponding reaches in ft.

- **Percent Impervious:** The portion of the catchment's total surface area that is impervious, expressed as a percent value between 0 and 100. (See Section 3.2.1 for more details.)

- **Maximum Pervious Depression Storage:** Maximum depression storage on pervious surfaces in inches. (See Table 6-6).

- **Maximum Impervious Depression Storage:** Maximum depression storage on impervious surfaces in inches. (See Table 6-6).

- **Initial Infiltration Rate:** Initial infiltration rate for pervious surfaces the units of which are inches per hour. When entered without a decay coefficient and final infiltration rate, this value becomes a constant infiltration rate throughout the storm (not recommended). (See Table 6-7).

- **Horton's Decay Coefficient:** Exponential decay coefficient in Horton's equation in "per second" units. (See Table 6-7).

- **Final Infiltration Rate:** Final infiltration rate in Horton's equation in inches per hour. (See Table 6-7).

The following catchment parameters are optional inputs and are available to the user to account for the effects of directly connected/disconnected impervious areas:

- **DCIA Level:** Specifies the directly connected impervious area (DCIA) level of practice as defined in the Structural BMPs chapter in Volume 3 of the USDCM. The user may specify 0, 1 or 2 for the level of DCIA to model.

- **Directly Connected Impervious Fraction:** Defines the fraction of the total impervious area directly connected to the drainage system. Values range from 0.01 to 1.0.

- **Receiving Pervious Fraction:** Defines the fraction of total pervious area receiving runoff from the "disconnected" impervious areas. Values range from 0.01 to 1.0.

To assist in the determination of the time to peak and peak runoff for the unit hydrograph, the program computes the coefficients C_T, C_t and C_p; however, override values for these parameters can also be user-specified as an option. The algorithm described in the CUHP 2005 User Manual develops the unit hydrograph.

- **C_T:** An unmodified time to peak coefficient that relates the total imperviousness of a catchment to the time to peak.

- **C_t:** Area-adjusted time to peak coefficient obtained by applying an area correction to C_T
- **C_p:** Peak runoff rate coefficient determined from C_t and the peaking parameter, P.

The shaping of the unit hydrograph also relies on proportioning the widths at 50% and 75% of the unit hydrograph peak. The proportioning is based on 0.35 of the width at 50% of peak being ahead of the “time to peak” and 0.45 of the width at 75% of peak being ahead of the “time to peak.” These proportioning factors were selected after observing a number of unit hydrographs derived from the rainfall-runoff data collected by the USGS for UDFCD. It is possible for the user to override the unit hydrograph widths and the proportioning of these widths built into the program. For drainage and flood studies within UDFCD, the program values should be used. If the user has derived unit hydrographs from reliable rainfall-runoff data for a study catchment and can develop a “calibrated” unit hydrograph for this catchment, this option permits reshaping the unit hydrograph accordingly.

3.3.3 Catchment Delineation Criteria

UDFCD recommends an average catchment size of approximately 100 acres for master planning purposes. Catchments larger than 5 square miles should be subdivided into subcatchments and individual subcatchment storm hydrographs should be routed downstream using appropriate channel routing procedures such as the EPA’s SWMM model. The routed hydrographs are then added to develop a single composite storm hydrograph. See Table 6-1 for a description of catchment size limitations for CUHP.

The catchment shape can have a profound effect on the final results and, in some instances, can result in underestimates of peak flows. Experience with the 1982 version of CUHP has shown that, whenever catchment length is increased faster than its area, the storm hydrograph peak will tend to decrease disproportionately. Although hydrologic routing is an integral part of runoff analysis, the data used to develop CUHP are insufficient to say that the observed CUHP response with disproportionately increasing basin length is valid. For this reason, it is recommended to subdivide irregularly shaped or very long catchments (i.e., catchment length to width ratio of four or more) into more regularly shaped subcatchments. A composite catchment storm hydrograph can be developed using appropriate routing and by adding the individual subcatchment storm hydrographs.

3.3.4 Combining and Routing Subcatchment CUHP Hydrographs

When analyzing a number of subcatchments, it is necessary to combine and route the runoff hydrographs subcatchment to determine the flows and volumes throughout the system. CUHP software provides input parameters that identify to which junction in EPA SWMM each subcatchment’s hydrograph is to be linked and then generates an output file that SWMM recognizes as an external flow file. The CUHP User Manual covers all these features and more.

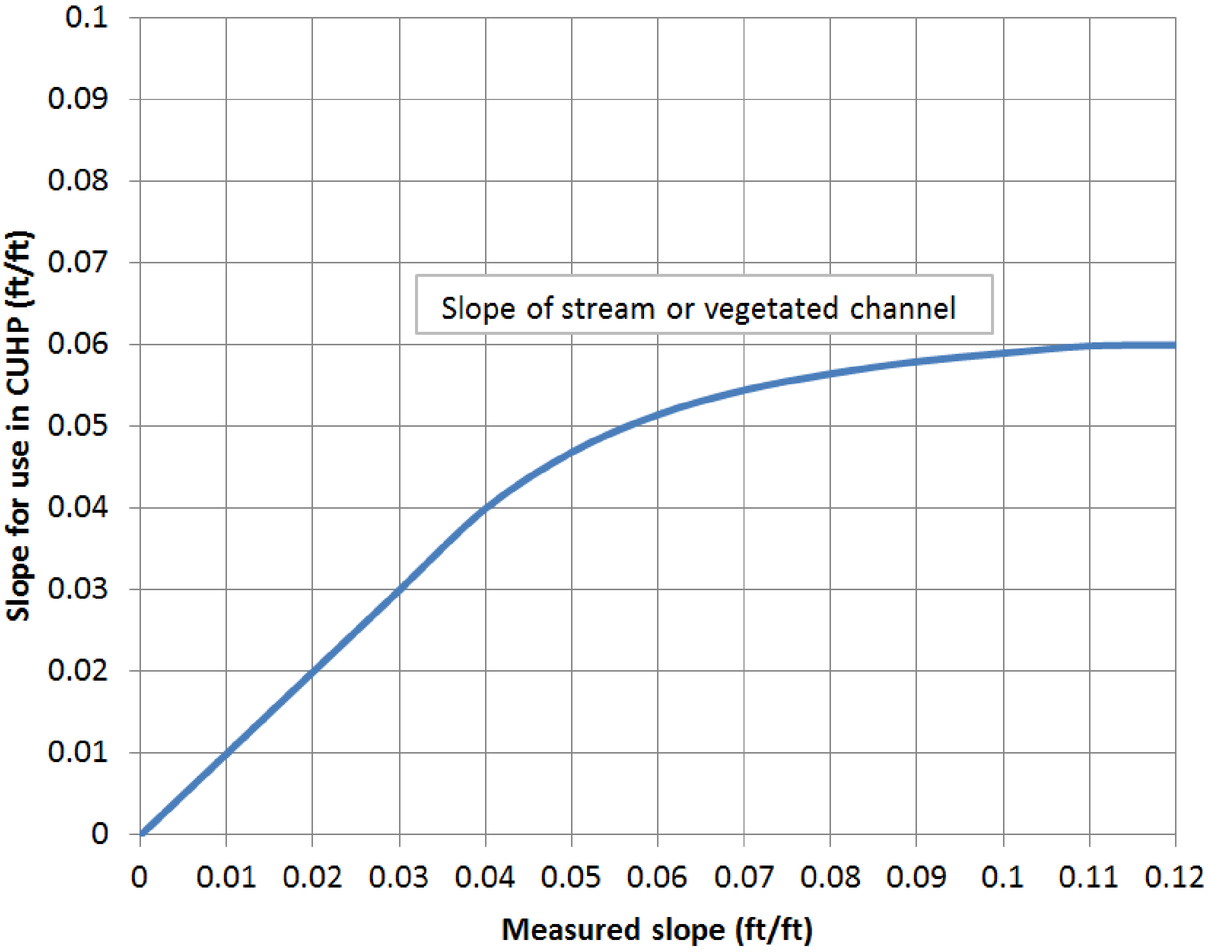


Figure 6-4. Slope correction for streams and vegetated channels

4.0 EPA SWMM And Hydrograph Routing

The Environmental Protection Agency's (EPA's) Stormwater Management Model (SWMM) 5 is a computer model that is used to generate surface runoff hydrographs from subcatchments and then route and combine these hydrographs. The procedure described here is limited to the routing of hydrographs generated using CUHP software. Originally this was done using UDSWM, a modified version of EPA SWMM runoff calculations designed to work with CUHP. In 2005, UDFCD adopted the use of EPA's SWMM 5.0 model and recommends its use for all future hydrology studies.

The purpose of the discussion of SWMM in this chapter is to provide general background on the use of the model with CUHP software to perform more complex stormwater runoff calculations using SWMM. Complete details about this model's use and specifics of data format are provided in the user manual for SWMM. That software, user manual, and other information about EPA's SWMM may be downloaded from http://www2.epa.gov/water-research/storm-water-management-model-swmm.

4.1 Software Description

SWMM represents a watershed by an aggregate of idealized runoff planes, channels, gutters, pipes and specialized units such as storage nodes, outlets, pumps, etc. The program can accept rainfall hyetographs and make a step-by-step accounting of rainfall infiltration losses in pervious areas, surface retention, overland flow, and gutter flow leading to the calculation of hydrographs. However, this portion of the model is normally not used by UDFCD because the resulting peak flows and volumes of runoff would not be calibrated to UDFCD regional rainfall-runoff observations the way CUHP storm hydrographs are. Instead, the calculation of hydrographs for each subcatchment is carried out using the CUHP software. If the user wants to use SWMM to calculate runoff, the model must be calibrated against the CUHP calculations for each subcatchment being studied.

After CUHP software is used to calculate hydrographs from a number of subcatchments, the resulting hydrographs from these subcatchments can be combined and routed through a series of links (i.e., channels, gutters, pipes, dummy links, etc.) and nodes (i.e., junctures, storage, diversion, etc.) to compute the resultant hydrographs at any number of design points within the watershed.

4.1.1 Surface Flows and Flow Routing Features

Stormwater runoff hydrographs generated using CUHP can be routed through a system of stormwater conveyance, diversion, storage, etc. elements of a complex urban watershed. In setting up the SWMM model, it is critical that overflow links for storm sewers and diversion junctions are provided in the model. The combination of these allows the user to model flows accurately when pipes and/or channels that do not have the capacity to convey higher flows, at which time the excess flows are diverted to the overflow channels. This method avoids "choking" of the flow and errors in the calculated peak flow values downstream are prevented.

There are several types of conveyance elements that one can select from a menu in SWMM. One element that is now available, that was not available in older versions, is a user-defined irregular channel cross-section, similar to the way cross-sections are defined in HEC-RAS. This makes the model very flexible in modeling natural waterways and composite man-made channels. For a complete description of the routing elements and junction types available for modeling, see the SWMM User's Manual published by EPA and available from their website mentioned earlier.

4.1.2 Flow Routing Method of Choice

UDFCD recommends the use of kinematic wave routing as the “routing” option in SWMM for planning purposes. Flood flows are generally dominated by kinematic waves (USACE 1993). Dynamic wave routing for most projects, does not improve the accuracy of the runoff estimates, and can be much more difficult to implement because it requires more information to describe the entire flow routing system. Additionally, it has tendencies to become unstable when modeling the more complex elements and/or junctions. Much of the required detail may not even be available during the planning phase (e.g., location of all drop structures and their crest and toe elevations for which a node must be defined in the model).

The use of dynamic wave routing is appropriate when inertial and pressure forces are important and when evaluating complex existing elements of a larger system. It is an option that can also offer some advantages in final design and its evaluation, as it provides hydraulic grade lines and accounts for backwater effects.

4.2 Data Preparation for the SWMM Software

Use of SWMM requires three basic steps:

Step 1: Identify and define the geometries of the watershed, subcatchments, and conveyance/storage elements.

Step 2: Estimates of roughness coefficients and functional/tabular relationships for storage and other special elements.

Step 3: Prepare input data for the model.

4.2.1 Step 1: Method of Discretization

Discretization is a procedure for the mathematical abstraction of the watershed and of the physical drainage system. Discretization begins with the identification of drainage area boundaries, the location of storm drains, streets, and channels, and the selection of those routing elements to be included in the system. For the computation of hydrographs, the watershed may be conceptually represented by a network of hydraulic elements (i.e., subcatchments, gutters, pipes, etc.). Hydraulic properties of each element are then characterized by various parameters such as size, slope, and roughness coefficient.

Discretizing large catchments into smaller ones:

Discretizing large catchments into smaller ones often results in increased unit discharges. The following recommendations can help eliminate the effect of the increase to provide more realistic hydraulic routing through the conveyance network in the EPA SWMM:

- Carefully estimate the effective longitudinal channel slope instead of relying on the elevations at the two ends of each routing element. If there are drop structures or other forms of vertical offsets in the channel reach, the effective channel slope between drops should be used rather than an overall reach slope between endpoints.
- Select the irregular natural channel option in the SWMM conduit cross-section editor to accurately represent actual channel cross-sections rather than selecting general geometric channels. This will ensure a more accurate wetted perimeter.
- Use appropriate Manning’s n values that are reflective of the nuances in channel geometry and other flow controls along its reaches, namely those recommended in Section 7.2.3 of the *Open Channels* Chapter of the USDCM by following these guidelines:
    - For lined channels and pipes, increase Manning’s n value by 25% over what would normally be used for the design as described in Section 4.2.2 below.
    - For grass-lined, riprap-lined and natural channels use the higher range of the values for the appropriate type of channel reach as recommended in Table B.2. Manning's Roughness Coefficients for Various Boundaries of the FHWA publication HDS-4, Introduction to Highway Hydraulics.
    - Whenever HEC-RAS sections are available, use the roughness coefficients for the main channel and overbanks from those studies unless the values obtained from item 3.b above are higher.

4.2.2 Step 2: Estimate Coefficients and Functional/Tabular Characteristic of Storage and Outlets

For hydrologic routing through conveyance elements such as pipes, gutters, and channels, the resistance (Manning's *n*) coefficients should not necessarily be the same as those used in performing hydraulic design calculations. As a general rule, it was found that increasing the "typical" values of Manning's *n* by approximately 25 percent was appropriate when using UDSWM in the past and should be appropriate for use in SWMM as well. Thus, if a pipe is estimated to have $n = 0.013$ for hydraulic calculations, it is appropriate to use $n = 0.016$ in SWMM.

When modeling the hydrologic routing of natural streams, grass-lined channels, or riprap-lined channels in Colorado, estimate Manning's *n* for SWMM using Equation 6-8 (Jarrett 1984 and 1985).

$$n = 0.393\, S^{0.38} R^{-0.16}$$

Equation 6-8

Where:

n = Manning's roughness coefficient

S = friction slope (ft/ft)

R = hydraulic radius (ft).

To estimate the hydraulic radius of a natural, grass-lined, or riprap-lined channel for Equation 6-8, use one-half of the estimated hydrograph peak flow to account for the variable depth of flow during a storm event.

SWMM does not have built-in shapes that define geometries of gutters or streets. The user can use the irregular shape option to define the shape of the gutter and street. For storage junctions, the user can define relationships such as stage vs. storage-surface area using mathematical functions or tables generated by the UD-Detention workbook tool or otherwise developed. For storage outlets or downstream outfalls, the user can use tables or functions to define their stage-discharge characteristics. As an alternative, the user can define geometries and characteristics for weirs and orifices and let the program calculate the functional relationships. Use of the weirs can sometimes be particularly troublesome when the dynamic wave routing option is used.

4.2.3 Step 3: Preparation of Data for Computer Input

The major preparation effort is forming a tree structure of all the runoff and conveyance elements and dividing the watershed into subcatchments. Develop the conveyance elements network using a watershed map, subdivision plans, and "as-built" drawings of the drainage system. Define pipes with little or no backwater effects, channels, reservoirs, or flow dividers as conveyance elements for computation by SWMM. Once the conveyance element system is set and labeled, use CUHP to generate an output text file that contains runoff hydrographs for all subcatchments. SWMM can use this file as an external “inflow interface file” to route the hydrograph data. Users should study the SWMM User’s Manual for complete details about data input preparation.

5.0 Other Hydrologic Methods

5.1 Published Hydrologic Information

UDFCD has prepared hydrologic studies for the majority of the major drainageways within UDFCD boundaries. These studies contain information regarding peak flow and runoff volume from the 2-year through 100-year storm events for numerous design points within the watershed. They also contain information regarding watershed and subcatchment boundaries, soil types, percentage imperviousness, and rainfall. The studies are available at www.udfcd.org. When published flow values are available from UDFCD, use these values for design unless there are compelling reasons to modify the published values.

5.2 Statistical Methods

Statistical analysis of measured streamflow data is also an acceptable means of hydrologic analysis in certain situations outside the UDFCD boundary. Statistical analysis should be limited to streams with a long period of flow data (30 years as a recommended minimum) where there have been no significant changes in land use in the tributary watershed during the period of the flow record (stationarity). Note that there is no generally accepted and widely used way to extrapolate calculated flow from a statistical analysis to estimate the flow for expected future watershed development conditions.

6.0 Software

UDFCD provides the following freeware to help with the calculations and protocols in the USDCM. See www.udfcd.org.

The Colorado Urban Hydrograph Procedure is a macro-enabled Excel workbook, titled CUHP.

An Excel workbook has been prepared to facilitate runoff calculations using the Rational Method, namely, UD-Rational (Guo 1995). Inputs needed include catchment area, runoff coefficient, 1-hour point rainfall depth, and flow reach characteristics (length, slope, and type of ground surface). The workbook then calculates the peak runoff in cfs.

The Rational Method can be used to design the storm drains with the aid of the UD-Sewer software or similar software. This software will pre-size storm drains using the same input mentioned for UD-Rational, except that it permits definition of existing links and that it also checks to ensure that the most critical portions of the catchment are accounted for in sizing the drains. After sizing the drains, or for an existing system, it can be used to analyze the hydraulic and energy grade lines of the system and will generate a profile plot of the sewer, ground line, hydraulic grade line and energy grade line.

UD-Rain is an Excel workbook that helps the user find the rainfall depth-duration-frequency and intensity-duration-frequency curves for any region in Colorado based on site elevation. It also helps the user develop 2-hour design storm distributions for use with CUHP or other models based on the protocols described in the USDCM. It will generate design storm hyetographs for small catchments (i.e., < 5 sq. mi.) all the way up to ones that are 75 sq. mi. in size, using area correction factors for the latter.

The latest release of the EPA SWMM software is available for downloading from EPA’s web site at http://www2.epa.gov/water-research/storm-water-management-model-swmm.

Users of these software packages should check for updates on a regular basis. Updates and enhancements are constantly under development.

7.0 Examples

7.1 Rational Method Example 1

Find the 100-year peak flow rate for a 60-acre catchment in an undeveloped grassland area located in Brighton. The upper 400 feet of the catchment is sloped at 2%, the lower 1,500 feet is grassed waterway that is sloped at 1%. The area has type C soils.

From NOAA Atlas 14, the 1-hour point precipitation value is 2.55 inches. The imperviousness is 2% (or 0.02) based on Table 6-3 and using the category "Undeveloped Areas, historic flow analysis."

Determine C_5 from Table 6-4:

$$C_5 = 0.82i + 0.035$$

$$C_5 = 0.82(0.02) + 0.035$$

= 0.05

Determine t_i from Equation 6-3:

$$t_i = \frac{0.395(1.1 - C_5)\sqrt{L_i}}{S_o^{\,0.33}}$$

$$t_i = \frac{0.395(1.1 - 0.05)\sqrt{400}}{(0.02)^{0.33}}$$

t_i = 30.2 minutes

Find t_t from Equation 6-4:

$$t_t = \frac{L_t}{60V_t} = \frac{L_t}{60K\sqrt{S_o}}$$

From Table 6-2, K = 15 (grassed waterway), S_o = 0.01 and L=1500 feet from problem statement

$$t_t = \frac{1500}{60(15\sqrt{0.01})}$$

t_t = 16.7 minutes

From Equation 6-2:

$$t_c = t_i + t_t$$

t_c = 30.2 + 16.7

t_c = 46.9 minutes

Note: The first design point time of concentration, Equation 6-5, does not apply for this example because the tributary area is undeveloped and less than 20% impervious.

Determine C_{100} from Table 6-4:

$$C_{100} = 0.41i + 0.484$$

$$C_{100} = 0.41(0.02) + 0.484$$

C_{100} = 0.49

Determine rainfall intensity, I, from Equation 4-3 (from the *Rainfall* chapter)

$$I = \frac{28.5P_1}{(10+t_c)^{0.786}}$$

$$I = \frac{28.5(2.55)}{(10+46.9)^{0.786}}$$

I = 3.03 in/hr

Determine Q from Equation 6-1:

$$Q = CIA$$

$$Q = (0.49)(3.03)(60)$$

Q = 89 cfs

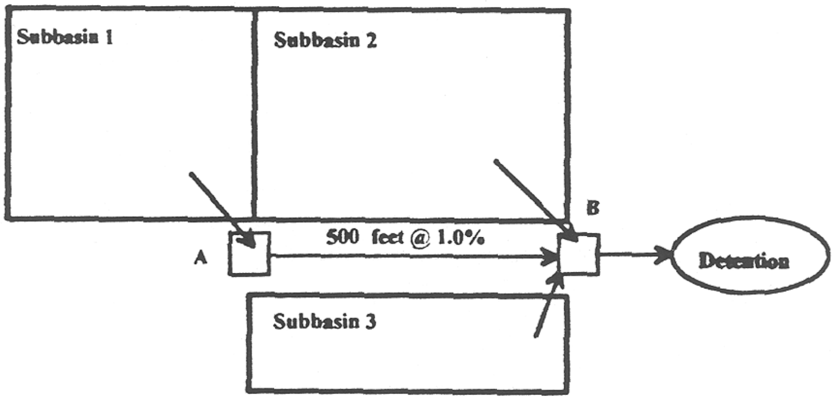
Alternately, use the UD-Rational Excel workbook to calculate the peak flow rate.

7.2 Rational Method Example 2

A watershed contains three subcatchments in the City of Denver. The drainage system collects Subcatchment 1 at Point A, and Subcatchments 2 and 3 at Point B, and then drains into a detention system. Determine the 10-year peak discharge at Point B using the watershed parameters summarized in the table. Assume that the imperviousness is 98 percent.

Subcatchment	Drainage Area A (acres)	Runoff Coefficient C	Time of Concentration T_c (minutes)
1	2.00	0.55	15.00
2	5.00	0.65	22.00
3	1.50	0.81	12.00

As shown in the figure, there are three flow paths to reach Point B. Their flow times are:



From Subcatchment 1: The flow time includes the time of concentration of Subcatchment 1, and the flow time from Point A to Point B through the street. The flow time from Subcatchment 1 to Point B is the sum of the time of concentration of Subcatchment 1 and the flow time through the 500-foot gutter:

$$t_1 = t_i + t_t$$

t_i = 15 minutes

$$t_t = \frac{L_t}{60V_t} = \frac{L_t}{60K\sqrt{S_o}}$$

$$t_1 = 15 + \frac{500}{60(20)\sqrt{0.01}} = 19.2 \text{ minutes}$$

From Problem Statement for Subcatchment 2: t_2 = 22 minutes

From Problem Statement for Subcatchment 3: t_3 = 12 minutes

At Point B, the design rainfall duration t_d = max (t_1, t_2, t_3) = 22 minutes.

The 10-year design rainfall intensity for Denver is (from Equation 5-1 in the *Rainfall* chapter):

$$I = \frac{28.5 P_1}{(10 + t_c)^{0.786}}$$

$$I = \frac{28.5\,(1.33)}{\left(10 + 22\right)^{0.786}} = 2.48 \text{ in/hr}$$

Area-weighted runoff coefficient, $C_{composite}$ calculation shown below for all of the areas that drain to Point B:

$$C_{composite} = \frac{(C_1 A_1 + C_2 A_2 + C_3 A_3)}{(A_1 + A_2 + A_3)}$$

$$C_{composite} = \frac{((0.55)(2) + (0.65)(5) + (0.81)(1.5))}{(2 + 5 + 1.5)} = 0.65$$

The 10-year peak discharge is:

Q = CIA = (0.65)(2.48)(8.5) = 13.70 cfs

8.0 References

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