Section 600 Runoff
Table of Contents

List of Tables

Section 600 Runoff

601 INTRODUCTION

This section will provide information and guidance on the five models approved to predict storm runoff: the Rational Method, the Colorado Urban Hydrograph Procedure (CUHP) developed by the UDFCD, the Storm Water Management Model created by the U.S. EPA (EPA-SWMM), the Hydrologic Modeling System by the U.S. Army Corps of Engineers Hydraulic Engineering Center (HEC-HMS), and StreamStats created by the USGS. All new development must use one of the first four methods to complete a detailed analysis unless published flows already exist. An exception will be made for a single-family dwelling, which may use StreamStats to estimate flow rates for design of a private driveway bridge or other drainage facilities.

For most large projects, CUHP will be used in conjunction with EPA-SWMM. For most small projects, the Rational Method will be used. The detailed computational techniques for these methods are presented in this section. The information contained in this section was largely adapted from the USDCM (UDFCD, 2016) for use in Boulder County. If the UDFCD revises the information below in future updates, those updates shall apply.

602 RATIONAL METHOD

For improvements with a total drainage area less than 90 acres, peak runoff may be calculated using the Rational Method. Despite its limitations, no other practical drainage design method has the same level of general acceptance. The Rational Method, when properly understood and applied, can produce satisfactory results for the design of urban storm drainage facilities.

One shortcoming of the Rational Method is that only one point on the runoff hydrograph is computed, the peak runoff rate. Projects that require a full runoff hydrograph will need to use CUHP or EPA SWMM. Another disadvantage is the difficulty of routing both the surface and piped flows where they have been separated by a storm sewer system. In general, this level of sophistication is not warranted, and a conservative assumption is made that the entire routing is in the storm drain system.

Finally, while the Rational Method can be used for basins up to 90 acres, this size limitation is for the sum of all the subbasins and not on the size of a single basin. The maximum size of any single basin should not exceed 15 acres for offsite flows analysis and 5 acres for onsite flow analysis. These subbasin sizes are based on typical gutter capacity for the onsite analysis and the minimum size storm drain for the offsite analysis.

602.1 Rational Method Formula

The formula for the Rational Method is shown in Equation 600.1.

$$Q = CIA \tag{600.1}$$

where

$Q =$ peak discharge $\left(\text{cubic feet per second } \left[\text{ft}^3/\text{s}\right]\right)$

$C =$ runoff coefficient

$I =$ average intensity of rainfall for a duration equal to the time of concentration (in/hr)

$A =$ drainage basin area (acres)

The basic assumptions made when applying the Rational Formula are the following:

1. The computed maximum rate of runoff to the design point is a function of the average rainfall rate over the time of concentration to that point for the given return period.
2. The maximum rate of rainfall occurs during the time of concentration, and the design rainfall depth during the time of concentration is converted to the average rainfall intensity for the time of concentration.
3. The maximum runoff rate occurs when the entire area is contributing flow. However, this assumption has been modified from time to time when local rainfall/runoff data was used to improve calculated results.

602.2 Time of Concentration

One of the basic assumptions of the Rational Method is that runoff is a function of the average rainfall rate during the time required for water to flow from the most distant part of the drainage basin to the point under consideration. The time of concentration relationships in this section are based in part on rainfall-runoff data collected in the Denver area, and were developed in conjunction with the runoff coefficients that are also recommended in this section.

The time of concentration includes an overland travel time, t_i, and a channelized travel time, t_t, typically in a swale, storm drain, paved gutter, or channel. Overland travel time, also known as initial travel time, will vary with distance, surface slope, depression storage, surface cover, antecedent rainfall, and infiltration capacity of the soil. Channelized travel time can be estimated from the hydraulic properties of the swale, storm drain, gutter, or channel. The time of concentration is calculated using Equation 600.2 for both urban and non-urban areas.

$$t_c = t_i + t_t \tag{600.2}$$

where

$t_c =$ time of concentration (minutes)

$t_i =$ initial or overland travel time (minutes)

$t_t =$ channelized travel time in a swale, storm drain, paved gutter, and channel (minutes).

Initial or overland travel time is calculated using Equation 600.3.

$$t_i = \frac{0.395\left(1.1 - C_5\right)\sqrt{L}}{S^{0.33}} \tag{600.3}$$

where

t_i = overland or initial flow time (minutes)

C_5 = runoff coefficient for 5-year frequency from Table 600-6

L = length of overland flow (ft), 500 foot maximum for nonurban, 300 foot maximum for urban

S = average basin slope along the length of overland flow (ft/ft).

In some urban watersheds, the overland flow time may be very short as flows quickly channelize.

To calculate channelized travel time, the hydraulic properties of the swale, storm drain, paved gutter, or channel are first used to calculate flow velocity using Equation 600.4.

$$t_t = \frac{L_t}{60K\sqrt{S_0}} = \frac{L_t}{60V_t} \tag{600.4}$$

where

t_t = channelized travel time (minutes)

L_t = length of channel (ft)

K = conveyance coefficient from Table 600-1

S_0 = channel slope (ft/ft)

V_t = velocity (ft/sec).

Table 600-1. Conveyance Coefficient K (UDFCD, 2016)

Type of Land Surface	K
Heavy meadow	2.5
Tillage/field	5.0
Short pasture and lawns	7.0
Nearly bare ground	10
Grassed waterway	15
Paved areas and shallow paved swales	20

The total time of concentration can then be calculated by adding initial travel time to channelized travel time as shown in Equation 600.2.

For urban areas, the time of concentration calculated using Equation 600.2 should be checked against Equation 600.5 and the lesser time of concentration shall be sued.

$$t_c = \left(18 - 15i\right) + \frac{L}{60\left(24i + 12\right)\sqrt{S_0}} \tag{600.5}$$

where

$t_c =$ maximum time of concentration for an urban watershed (minutes)

$L_t =$ combined length of overland and channelized flow (ft)

$i =$ imperviousness (expressed as a decimal)

$S_0 =$ slope of flow path (ft/ft).

Equation 600.5 was developed as part of a calibration study between the Rational Method and CUHP. Typically, Equation 600.5 will result in the lesser time of concentration and will govern in an urban environment. Furthermore, a minimum total time of concentration of 10 minutes should be used for non-urban watersheds, and a minimum total time of concentration of 5 minutes should be used for urbanized areas.

When using the Rational Method, it may be worth checking runoff peaks for multiple scenarios in each basin. Sometimes a lower portion of the catchment or areas of high imperviousness will produce a larger peak than is computed for the whole basin. This occurs most often when the basin is long or the upper portion contains grassy parkland and the lower portion is developed urban land.

602.3 Intensity

Rainfall intensity, I, is the maximum average rainfall rate in inches per hour for a duration equal to the time of concentration. Each return period will have a different intensity for a given time of concentration. After the design return period has been selected and the time of concentration has been calculated, Equation 500.1 can be used to determine the appropriate intensity. Refer to Section 500 for additional information.

602.4 Runoff Coefficient

The runoff coefficient, *C*, represents the effects of infiltration, evaporation, retention, routing, and interception, all of which affect peak runoff rates. The runoff coefficient varies by return period as well. The methodology to determine the runoff coefficient presented in this Section is adapted from the USDCM. The coefficients presented were calibrated for the Denver and Boulder area and may not be valid for use in other locations.

Runoff coefficients are influenced by soil type, imperviousness, and storm return period. Soil is categorized into four hydrologic groups by the NRCS – Types A, B, C, and D – based on water infiltration rates. Recommended imperviousness percentages, i, are listed in Table 600-2. Runoff coefficient equations are listed in Table 600-3 by soil type and storm return period. Note that imperviousness values from Table 600-2 must be converted to a decimal before being used to calculate runoff coefficients. Runoff coefficients are also presented and organized by imperviousness, soil type, and return period in Table 600-6 at the end of this section.

Table 600-2. Recommended Percentage Imperviousness Values (UDFCD, 2016)

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 is not defined)	45
Streets	
Paved	100
Gravel (packed)	40
Drive and walks	90
Roofs	90
Lawns, sandy soil	2
Lawns, clayey soil	2

Table 600-3. Runoff Coefficient Equations Based on NRCS Soil Group and Return Period (UDFCD, 2016)

NRCS Soil Type	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	$C_{C/D} = 0.89i$	$C_{C/D} = 0.87i + 0.052$	$C_{C/D} = 0.74i + 0.2$	$C_{C/D} = 0.64i + 0.31$	$C_{C/D} = 0.54i + 0.418$	$C_{C/D} = 0.45i + 0.508$

where

$$i = \text{imperviousness } (\text{expressed as a decimal}) \ (\text{see Table 600-2})$$

$$C_A = \text{Runoff coefficient for NRCS Type A soils}$$

$$C_B = \text{Runoff coefficient for NRCS Type B soils}$$

$$C_{C/D} = \text{Runoff coefficient for NRCS Type C and D soils.}$$

602.5 Basin Delineation

The first step in applying the Rational Method is to delineate all subbasins using available contour and topographic data. Basins delineated by computer programs should have their boundaries verified. Basin delineations should include all area both tributary to and within the area of study. Field checks should be performed for each basin when feasible, or where available topography does not offer definitive boundaries.

The major storm drainage basin may not always coincide with the minor storm drainage basin. This is often the case in urban areas where minor storm flow may stay within a curb and gutter section, but a portion of the major storm flow will overtop the back of curb or street crown and flow into an adjacent subbasin.

602.6 Major Storm Analysis

Typical application of the Rational Method assumes that all of the runoff is collected by the storm sewer. For the minor storm design, the time of concentration is dependent upon the flow time in the sewer. However, during the major storm, storm drains will most likely be at capacity and will not be able carry the additional water flowing to the inlets. This additional water then flows overland past the inlets, generally at a lower velocity than the flow in the storm sewers. Using a separate time of concentration analysis for pipe flow and surface flow during the major storm event is acceptable but very complex and most likely not worth the effort. The simplified approach of using the minor storm time of concentration for all frequency analysis is acceptable for Boulder County.

602.7 UD-Rational

UD-Rational is a macro-enabled Microsoft Excel spreadsheet published by the UDFCD to assist with using the Rational Method. The spreadsheet can calculate the runoff coefficient, time of concentration, and rainfall intensity. The spreadsheet is available at the UDFCD website (www.udfcd.org).

603 COLORADO URBAN HYDROGRAPH PROCEDURE

CUHP is a method of hydrologic analysis based upon the unit hydrograph principle. It has been developed and calibrated using rainfall-runoff data collected in Colorado, mostly in the Denver and Boulder metropolitan areas. This section provides general background information on the use of the computerized version of CUHP to calculate runoff. Additional information on the various parameters discussed in this section can be found in the USDCM.

CUHP has been created as a Microsoft Excel based program by the UDFCD. The program is commonly used in conjunction with EPA SWMM to route flows from and through multiple subbasins, or subcatchments, to a common design point. The latest versions of CUHP and the associated users' manual are available on the UDFCD website (*www.udfcd.org*).

603.1 Pervious and Impervious Areas

The urban landscape comprises both pervious and impervious surfaces. The degree of imperviousness is the primary variable within the program that affects the total volume and rate of runoff. The estimated future imperviousness is typically used for design purposes. For subcatchments with nonhomogeneous imperviousness, the subcatchment area-weighted average imperviousness should be used. CUHP can also define the percentage of impervious area directly or indirectly connected to the drainage system and the percentage of pervious area that receives runoff from impervious areas. The CUHP users' manual contains additional information on this aspect of the program.

603.2 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. Depression losses include water intercepted by vegetation and imperfections in pavement, roofs, or other surfaces. CUHP requires depression loss depths in inches to calculate runoff. Table 600-4, adapted from the USDCM, can be used as a guide for estimating depression losses to be entered into CUHP.

Table 600-4. Typical Depression Losses for Various Land Covers

Land Cover	Range	Recommended
Impervious		
Large paved areas	0.05–0.15	0.1
Roofs, flat	0.1–0.3	0.1
Roofs, slopes	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

Note: All values are in inches for use with CUHP.

603.3 Infiltration

The flow of water into the soil surface is called infiltration. NRCS soil type is the most important factor in determining the infiltration rate. Horton’s equation is used to model infiltration within CUHP and is described further in the USDCM. Recommended parameters for Horton’s equation are provided in Table 600-5, adapted from the USDCM.

Table 600-5. Recommended Horton’s Equation Parameter

NRCS Hydrologic Soil Group	Infiltration (inches/hour)		Decay Coefficient
	Initial	Final	
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

603.4 Rainfall

A 2-hour design storm is required to use CUHP. It can be created automatically within CUHP using the 1-hour point rainfall depth obtained in accordance with Section 500. When using an area-corrected rainfall distribution, the 6-hour point depth rainfall is also required. CUHP will then automatically create design storms longer than 2 hours as required for area correction. The user can also enter a previously created hyetograph.

603.5 Catchment Parameters

The following basin and hydrologic parameters are required by CUHP. The units listed are the defaults used by CUHP.

1. Area – Catchment area in square miles
2. Target Node – EPA SWMM node that corresponds to CUHP subcatchment; only required if using EPA SWMM in conjunction with the CUHP model
3. Raingage – CUHP design storm hyetograph
4. Length to Centroid – Distance in miles from the subcatchment outlet along the main drainageway path to the nearest point on the drainageway path to the subcatchment centroid
5. Length – Distance in miles from the subcatchment outlet along the main drainageway path to the furthest point of the subcatchment
6. Slope – Length-weighted, average slope of the subcatchment in feet per foot. Vegetated channels with slopes greater than 4 percent must be adjusted according to the procedure described in the USDCM
7. Percent Imperviousness – The portion of a subcatchment’s total surface area that is impervious, represented as a percent value between 0 and 100

8. Maximum Depression Storage – Pervious and impervious depression storage in inches
9. Horton's Infiltration Parameters – Initial infiltration rate (inches/hour), decay coefficient (dimensionless), and final infiltration rate (inches/hour) for soil within the subcatchment.

In addition to the parameters listed above, CUHP provides the user with optional overrides for C_T, C_t, C_p, hydrograph shape, directly connected impervious fraction, and receiving pervious fraction. The program can also verify that parameters are within recommended limits. The user should take advantage of this functionality to ensure results from the model are valid.

603.6 Catchment Delineation Criteria and Routing

The maximum size of a subcatchment is limited to 5 square miles. Whenever a larger subcatchment is studied, it should be subdivided into subcatchments of 5 square miles or less, and individual subcatchment storm hydrographs should be routed downstream using appropriate channel routing procedures such as those used by EPA SWMM. For areas less than 90 acres, a 1-minute time step should be used. The subcatchment shape can have a profound effect on the results and, in some instances, can result in underestimating peak flows. Irregularly shaped or very long subcatchments with a length-to-width ratio of four or more should be subdivided into more regularly shaped subcatchments. CUHP can create interface files that allow EPA SWMM to route subcatchment hydrographs, calculating a composite storm hydrograph at each design point. The CUHP users' manual provides information on calibrating the CUHP model, interfacing CUHP with EPA SWMM, and running multiple scenarios.

604 STORM WATER MANAGEMENT MODEL

EPA SWMM is a computer model that will generate surface runoff hydrographs from subcatchments and then route and combine those hydrographs. The program can also route and combine subcatchment hydrographs created by CUHP and is particularly useful for projects that require multiple CUHP subcatchments. EPA SWMM and the users' manual can be obtained from the EPA website (*www.epa.gov/water-research/storm-water-management-model-swmm*) or via an internet search for "EPA SWMM."

604.1 Routing

EPA SWMM consists of a network of open channels, pipes, and specialized units such as diversion nodes, storage units, and pumps. When modeling a project with storm sewers or culverts that are undersized for the design storm it is critical to include overflow links and diversions nodes in the model at locations with undersized infrastructure. Failure to do so may result in peak flows being underestimated. The output of the model should be carefully examined to determine if the capacity of any links are being exceeded.

604.2 Routing Method

Three hydrograph routing algorithms are available within EPA SWMM. They include steady flow, kinematic wave, and dynamic wave. The kinematic wave algorithm provides an acceptable degree of accuracy and is recommended for most projects in the county. Steady flow is the simplest routing strategy and translates inflow hydrographs to the downstream end with no delay or change in shape.

Steady flow routing will typically overestimate peak flows and is not recommended. Dynamic wave routing is theoretically the most accurate method but requires a more refined model and tends to be unstable when analyzing complex systems. For most projects, the increase in accuracy is minimal and does not justify the extra time and effort required to create a stable model. Dynamic wave routing is not recommended.

605 HYDROLOGIC MODELING SYSTEM

HEC-HMS provides much of the same functionality as EPA SWMM and can be used to generate surface runoff hydrographs from subcatchments and route the hydrographs along a drainage network. CUHP will not directly interface with HEC-HMS, as it will with EPA SWMM. The program and users' manual is available at the HEC website (*http://www.hec.usace.army.mil/software/hec-hms*) or via an internet search for "HEC-HMS software."

606 STREAMSTATS

StreamStats is a web-based application developed by the USGS that provides an assortment of hydrologic tools in a visual, map-based format. The application can delineate the drainage basin for a given design point and calculate hydrologic parameters, including area, slope, and estimated precipitation. A regression analysis can be performed to estimate peak flows for the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return periods. All of the equations in Colorado StreamStats are documented in the report titled *Regional Regression Equations for Estimation of Natural Streamflow Statistics in Colorado* (Capesius and Stephens, 2009), available at (*http://pubs.usgs.gov/sir/2009/5136/pdf/SIR09-5136.pdf*) or via an internet search for "USGS Report 2009–5136."

Predicted error is provided with peak flow estimates, and can frequently exceed 100 percent. Because of the high margin of error of estimated flows, this method is not a substitute for detailed hydrologic analysis. StreamStats is a useful tool for the hydrologic engineer, but any results from the application should be used with care and in consideration of the uncertainties of the results and an appreciation for the risks associated with the project. Availability of regression equations and peak flows is limited to hydrologic basins with parameters that are within certain limits. StreamStats is available online at (*http://water.usgs.gov/osw/streamstats/colorado.html*) or via an internet search for "USGS StreamStats Colorado."

Flows generated by StreamStats can be used in Boulder County only for designs related to a single-family residence where published flows do not exist. For all other development, a detailed analysis is required using one of the other methods discussed in this Section if published flows do not exist for a given project location.

Table 600-6. Rational Method Runoff Coefficient, C (Page 1 of 2) (UDFCD, 2016)

Percentage Imperviousness	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
Type A NRCS Hydrologic Soil Group						
2	0.02	0.02	0.02	0.02	0.02	0.17
5	0.04	0.05	0.05	0.05	0.05	0.19
10	0.09	0.09	0.09	0.09	0.10	0.23
15	0.13	0.14	0.14	0.14	0.14	0.28
20	0.18	0.19	0.19	0.19	0.19	0.32
25	0.22	0.23	0.24	0.24	0.24	0.36
30	0.27	0.28	0.28	0.28	0.29	0.40
35	0.31	0.33	0.33	0.33	0.33	0.44
40	0.36	0.37	0.38	0.38	0.38	0.48
45	0.40	0.42	0.42	0.42	0.43	0.52
50	0.45	0.47	0.47	0.47	0.48	0.56
55	0.49	0.51	0.52	0.52	0.52	0.60
60	0.53	0.56	0.56	0.57	0.57	0.64
65	0.58	0.6	0.61	0.61	0.62	0.68
70	0.62	0.65	0.66	0.66	0.67	0.72
75	0.67	0.70	0.71	0.71	0.71	0.76
80	0.71	0.74	0.75	0.76	0.76	0.80
85	0.76	0.79	0.80	0.80	0.81	0.84
90	0.80	0.84	0.85	0.85	0.86	0.88
95	0.85	0.88	0.89	0.90	0.90	0.92
100	0.89	0.93	0.94	0.94	0.95	0.96
Type B NRCS Hydrologic Soil Group						
2	0.02	0.02	0.14	0.24	0.38	0.46
5	0.04	0.05	0.17	0.27	0.39	0.48
10	0.09	0.09	0.21	0.30	0.42	0.50
15	0.13	0.14	0.25	0.34	0.45	0.53
20	0.18	0.19	0.29	0.37	0.48	0.55
25	0.22	0.23	0.33	0.41	0.51	0.58
30	0.27	0.28	0.37	0.44	0.54	0.60
35	0.31	0.33	0.41	0.48	0.57	0.63
40	0.36	0.37	0.45	0.51	0.60	0.65
45	0.40	0.42	0.49	0.55	0.63	0.67
50	0.45	0.47	0.53	0.58	0.66	0.70

Table 600-6. Rational Method Runoff Coefficient, C (Page 2 of 2) (UDFCD, 2016)

Percentage Imperviousness	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
55	0.49	0.51	0.57	0.62	0.69	0.72
60	0.53	0.56	0.61	0.65	0.72	0.75
65	0.58	0.60	0.65	0.69	0.75	0.77
70	0.62	0.65	0.69	0.72	0.78	0.80
75	0.67	0.70	0.73	0.76	0.81	0.82
80	0.71	0.74	0.77	0.79	0.84	0.85
85	0.76	0.79	0.81	0.83	0.87	0.87
90	0.80	0.84	0.85	0.86	0.89	0.90
95	0.85	0.88	0.89	0.90	0.92	0.92
100	0.89	0.93	0.94	0.94	0.95	0.94
Type C/D NRCS Hydrologic Soil Groups						
2	0.02	0.07	0.22	0.32	0.43	0.52
5	0.04	0.10	0.24	0.34	0.45	0.53
10	0.09	0.14	0.27	0.37	0.47	0.55
15	0.13	0.18	0.31	0.41	0.50	0.58
20	0.18	0.23	0.35	0.44	0.53	0.60
25	0.22	0.27	0.39	0.47	0.55	0.62
30	0.27	0.31	0.42	0.50	0.58	0.64
35	0.31	0.36	0.46	0.53	0.61	0.67
40	0.36	0.40	0.50	0.57	0.63	0.69
45	0.40	0.44	0.53	0.60	0.66	0.71
50	0.45	0.49	0.57	0.63	0.69	0.73
55	0.49	0.53	0.61	0.66	0.72	0.76
60	0.53	0.57	0.64	0.69	0.74	0.78
65	0.58	0.62	0.68	0.73	0.77	0.80
70	0.62	0.66	0.72	0.76	0.80	0.82
75	0.67	0.70	0.76	0.79	0.82	0.85
80	0.71	0.75	0.79	0.82	0.85	0.87
85	0.76	0.79	0.83	0.85	0.88	0.89
90	0.80	0.83	0.87	0.89	0.90	0.91
95	0.85	0.88	0.90	0.92	0.93	0.94
100	0.89	0.92	0.94	0.95	0.96	0.96

607 REFERENCES

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