Chapter 3 – Runoff

3.1 Overview

The surface in a watershed is composed of pervious or impervious areas. The pervious surface is the area where water can readily infiltrate into the ground. The impervious surface is the area that produces direct runoff as soon as it rains. As urbanization occurs, impervious area increases. As a result, the total amount of runoff volume increases as well. In urban hydrology, the percentage of impervious area is the most sensitive parameter to the runoff generation.

Estimates of runoff flow rates and volumes for selected levels of protection provide the basis for the design of drainage facilities for the management of flood discharges and water quality in a drainage system. **This chapter provides criteria for design peaks and volumes and methods to calculate urban runoff generated in the Aspen area**. Methods described in this chapter include:

- the Rational Method applicable to watersheds less than 90 acres,
- the Colorado Urban Hydrograph Procedure (CUHP) developed for larger watersheds, and
- Storm Water Management Model (SWMM) Version 5 applicable to snowmelt runoff predictions or urban watersheds with on-site low impact treatments.

When the CUHP and SWMM models are used in tandem, they are referred to as CUHP/SWMM in this chapter.

3.2 Hydrologic Loss

Not all raindrops fall to the ground – some fall on vegetation and some is lost to evaporation. In addition, not all rainfall runs off – some is infiltrated in the soil and some is puddled and stored. The major hydrologic losses considered in the rainfall and runoff modeling techniques include *soil infiltration and depression loss.*

3.2.1 Soil Infiltration Loss

The penetration of water into the soil surface is called infiltration. 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. The *Natural Resources Conservation Service* (NRCS or SCS) has classified soils into four hydrologic types as (SCS 1983):

Type A Soil—Soils having high infiltration rates such as sand and gravel.
Type B Soil—Soils having moderate infiltration rates such as loamy soils.
Type C and D Soil—Soils having very slow infiltration such as clay soils.

Figure 3.1 depicts the hydrologic soil group (HSG) locations in Aspen. If the HSG is not known, but the soil type is, please refer to Appendix B, Table 3.2, which lists common soils found in the Aspen area. Note that it is rare to find HSG Type A soils in the Aspen area.

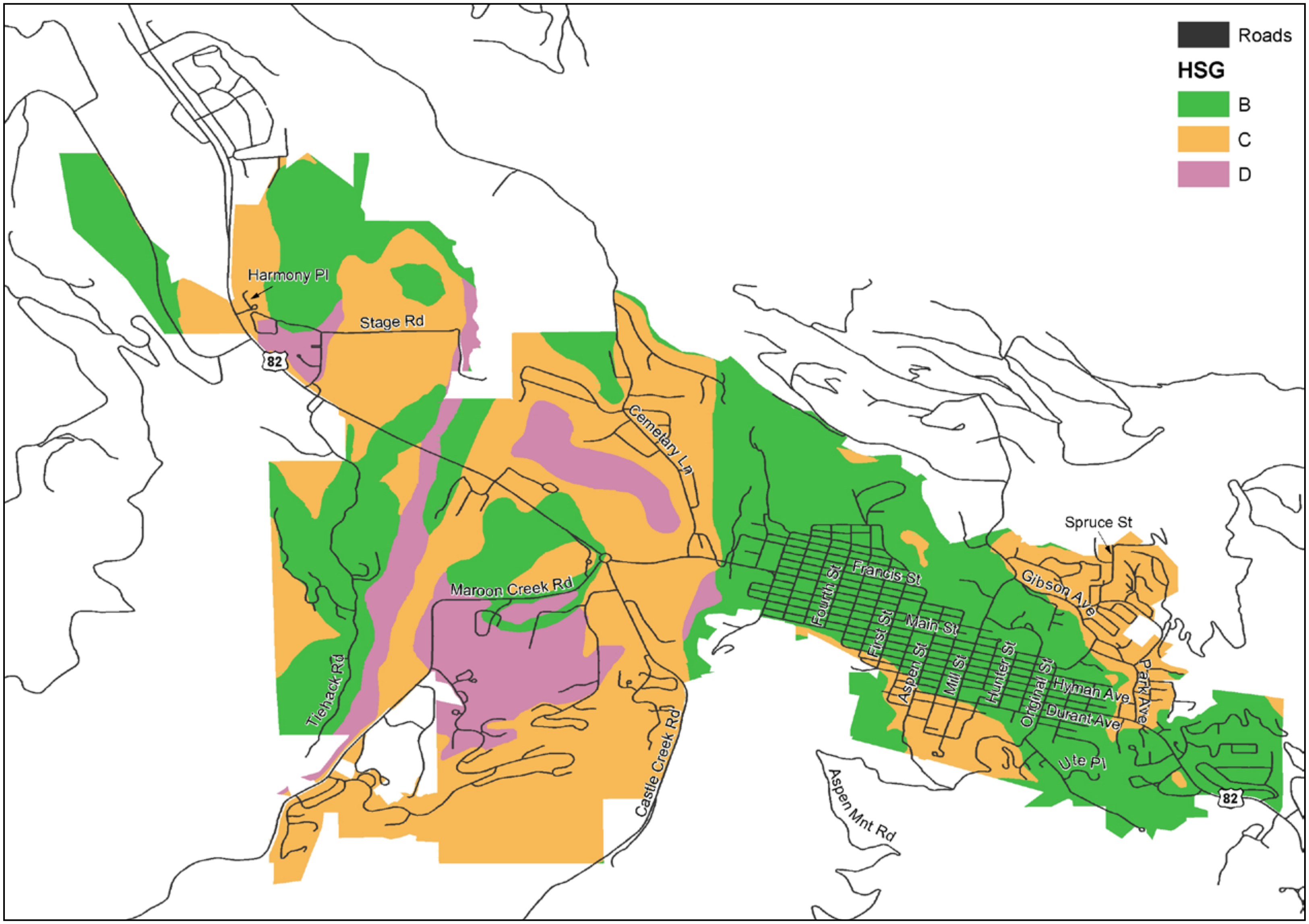


Figure 3.1 Natural Resource Conservation Service (NRCS) Soil Map for Aspen

An infiltration rate reflects the ability of the soil medium to absorb water. This parameter is usually given in inch per hour or millimeter per hour. Infiltration rates are described by a decay function with a high rate at the beginning of the event when the soil is dry, and a low rate when the soil becomes saturated.

Table 3.1 is recommended for design infiltration rates for use in CUHP and SWMM modeling, but is not needed in the Rational Method. When the watershed has several different types of soils, the representative infiltration rate can be determined as the area-weighted value.

Table 3.1 Infiltration Rates for Different Soil Groups (UDFCD 2001)

Soil Type	Initial Rate Inch/hr	Final Rate Inch/hr	Decay Coefficient 1/sec for CUHP	Decay Coefficient 1/hr for SWMM
A	5.0	1.0	0.0007	2.52
B	4.5	0.6	0.0018	6.48
C	3.0	0.5	0.0018	6.48
D	3.0	0.5	0.0018	6.48

3.2.2 Depression Loss

Depression losses account for the amount of water trapped in lowland areas, puddles, and potholes without running off. Depression loss is expressed as the lump sum of the entrapped water volume in inch per watershed. **Table 3.2** is a summary of the recommended depression capacity for use in CUHP/SWMM modeling. Depression losses are not needed for the Rational Method.

Table 3.2 Depression Losses for Various Land Uses (UDFCD 2001)

Land Cover	Range (inches)	Design Value (inches)
Large Paved Area	0.05-0.15	0.10
Flat Roofs	0.10 -0.30	0.10
Sloped Roofs	0.05-0.10	0.05
Lawn Grass	0.20- 0.50	0.03
Wooded Area	0.20- 0.60	0.40
Open Fields	0.20-0.60	0.40
Sandy Area		0.02
Loams		0.15
Clay		0.10

3.3 Selection of Runoff Prediction Methods

The **first step** in determining the flows at a design point is to obtain the representative topographic map of the tributary watershed and to **define the boundaries of all the relevant drainage basins**. Basins to be defined include all basins tributary to the area of study and sub-basins within the study area. Field checks and possibly field surveys must be completed before the preliminary stage of drainage planning. Flow diversions and irrigation canals must be also be investigated because they can transfer stormwater across the watershed boundaries.

All hydrologic methods have application limitations. The **second step, selection of runoff prediction method**, depends on design needs and watershed size. **For determining peak flows from watershed areas less than 90 acres, the Rational Method should be used.**

In large watersheds (>90 acres) the rainfall-runoff process is more complicated because hydrologic losses vary more and should not be simplified as they are in the Rational Method. Therefore, **for large watersheds hydrographs are needed and can be computed using CUHP** (Colorado Urban Hydrograph Procedure, recommended by UDFCD) **or SWMM** (Storm Water Management Model, recommended by the EPA). SWMM can also be used to determine snowmelt runoff hydrographs.

For examples, the Rational Method is sufficient for culvert sizing to pass the design peak flow from a watershed less than 90 acres. CUHP is required for detention basin designs because the procedure involves hydrograph routing. And SWMM can be used to study the alternatives for snow removal and redistribution along the street in the downtown area of the City of Aspen.

3.4 Rational Method

The Rational Method is a simplified hydrologic method developed for peak flow prediction in basins <90 acres only. It is applicable to street inlet sizing, sewer drain design, and single lot developments in the Aspen area. The Rational Method states (Kuichling, 1889):

Peak Flow **=** $Q_P = CIA$ **(Equation 3-1)**

Runoff Volume = $V_R = \frac{C}{12} P\,A$ **(Equation 3-2)**

Rainfall Depth **=** $P = \frac{T_d}{60} I$ **(Equation 3-3)**

in which,

Q_p = peak flow (peak runoff) in cubic feet per second (cfs),

I = rainfall intensity in inch/hour,

A = drainage area in acres,

C = runoff coefficient,

V_R = runoff volume in acre-ft,

P = rainfall depth in inches, and

T_d = rainfall duration (or time of concentration, *Tc*) in minutes.

The flow (*Qp*) must be calculated at each design point, starting at the upstream end of the watershed and proceeding downstream. Each watershed must be analyzed for the minor and major storm events. In most cases the minor event is the 10-year storm and the major event is the 100-year storm (see Chapter 5 – Detention for more details).

As indicated in Equation 3.1, the basic input parameters for the Rational Method include *watershed area*, *runoff coefficient*, and *design rainfall intensity***.** The rainfall intensity-duration–frequency (IDF) formula is applied to determine rainfall intensity (I). The rainfall IDF formula for the Aspen area can be found in Chapter 2 – Rainfall and is not covered in a subsection below.

The general procedure for Rational Method calculations for a single basin is described below with accompanying sections of this manual in *italics*.

1. Delineate the basin boundary. Measure its area. *Section 3.3.1*

2. Identify the soil type(s). *Figure 3.1*
3. Determine the runoff coefficient, C. *Section 3.4.2*
4. Define the flow path from the upper-most portion of the basin to the design point. This flow path should be divided into reaches of similar flow type (e.g., overland flow, shallow swale flow, gutter flow, etc.). The length and slope of each reach should be measured. *Section 3.4.3*
5. Determine the time of concentration, Tc, for the catchment. *Section 3.4.3*
6. Find the rainfall intensity, I, for the design storm using the calculated Tc and the rainfall intensity-duration-frequency curve. *Chapter 2, Section 2.3*
7. Calculate the peak flow rate from the watershed. *Equation 3-1*
8. When calculating 1-hour design storm volumes, $t_c=t_d=60$ minutes. *Equation 3-2.*

3.4.1 Watershed Area

The watershed drainage boundary lines are determined by grading and slopes - the pavement slopes, locations of downspouts and inlets, paved and unpaved yards, grading of lawns, and many other features found on the urban landscape. The tributary area to a design point can be outlined on the topographic map using Geographic Information System (GIS), or AutoCAD-based methods. The area may also be determined through the use of planimetric-topographic maps, supplemented by field surveys where topographic data has changed or where the contour interval is too coarse to distinguish the direction of flow. An urban watershed is often developed for multiple purposes. Therefore, it can be divided into smaller sub-areas based on the land uses and types of soils.

3.4.2 Runoff Coefficients and Percent Imperviousness for Land Uses

For convenience, the runoff coefficient, C, is derived to represent the ratio of runoff to rainfall volumes during the event. The determination of C mainly depends on the soil type, watershed imperviousness and storm event frequency.

The surface of a watershed is composed of pervious or impervious areas. As urbanization occurs, hard (impervious) surfaces increase, decreasing the amount of precipitation that infiltrates and increasing the amount that runs off. Impervious areas, A_i, in the tributary area can be determined based on the site plan, including roofs, sidewalks, drives, etc. The overall imperviousness of the drainage basin is calculated by dividing the impervious area in the drainage basin by the total area of the drainage basin.

Gravel parking areas, storage areas, and access drives as proposed on site improvement plans, should be analyzed as impervious surface. This is due to a history of gravel areas being compacted or paved over time by property owners and the resulting adverse impacts on the stormwater management facilities and adjacent properties.

As stated earlier, drainage basins can be divided into smaller sub-areas based on the land uses and types of soils. For mixed land uses, the area-weighted method is recommended to derive the representative runoff coefficient for the entire watershed.

For determination of *C,* identify the hydrologic soil group of soils within the basin and the imperviousness of the basin. Use the tables from UDFCD Urban Storm Drainage Criteria Manual Volume 1 copied below to determine the runoff coefficient for the appropriate storm event.

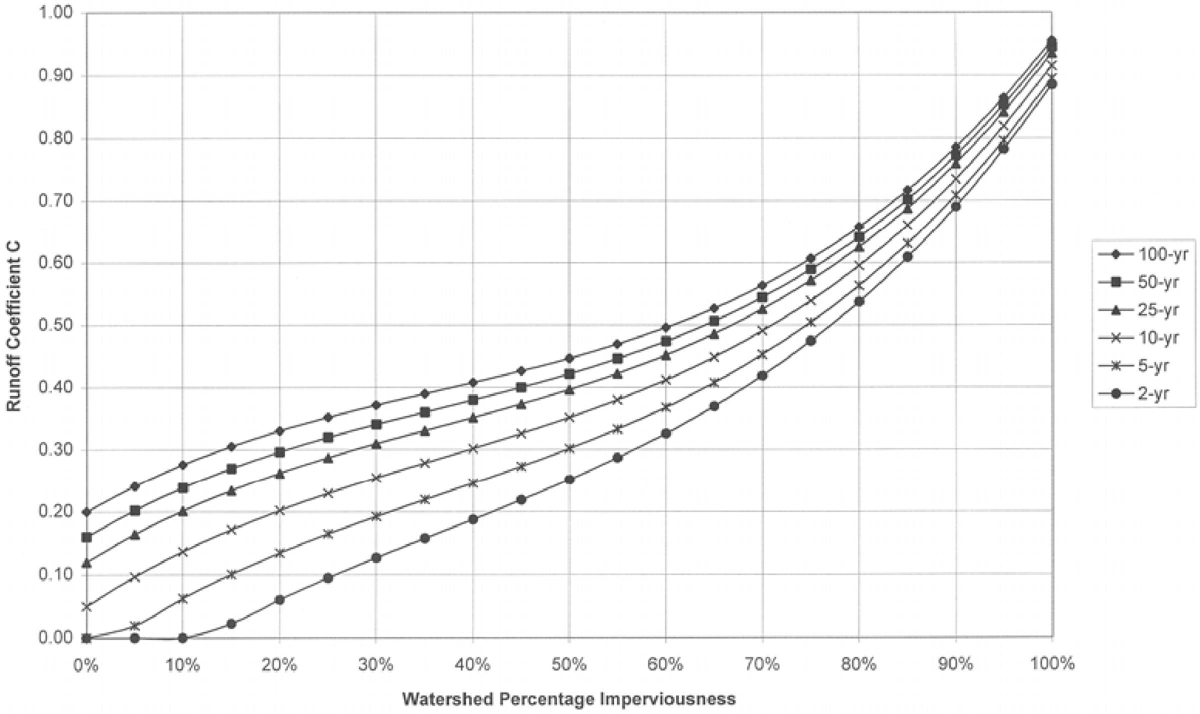


Figure 3.2 – Runoff Coefficients for NRCS Hydrologic Soil Group A

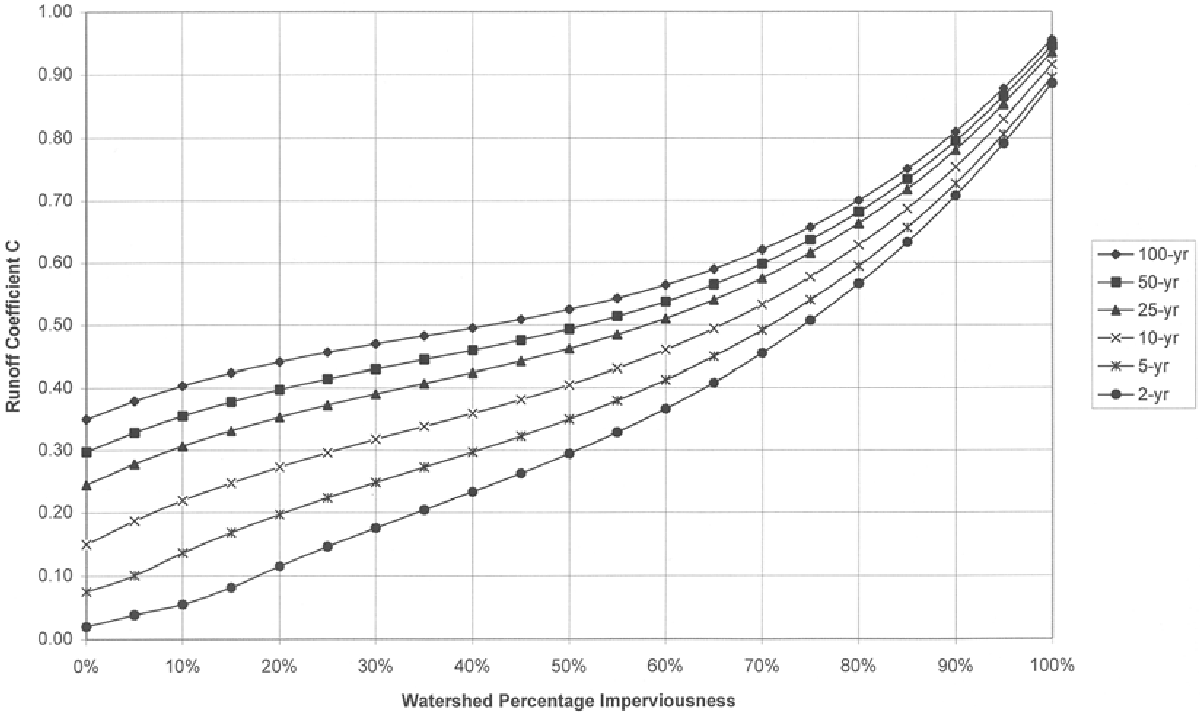


Figure 3.3 – Runoff Coefficients for NRCS Hydrologic Soil Group B

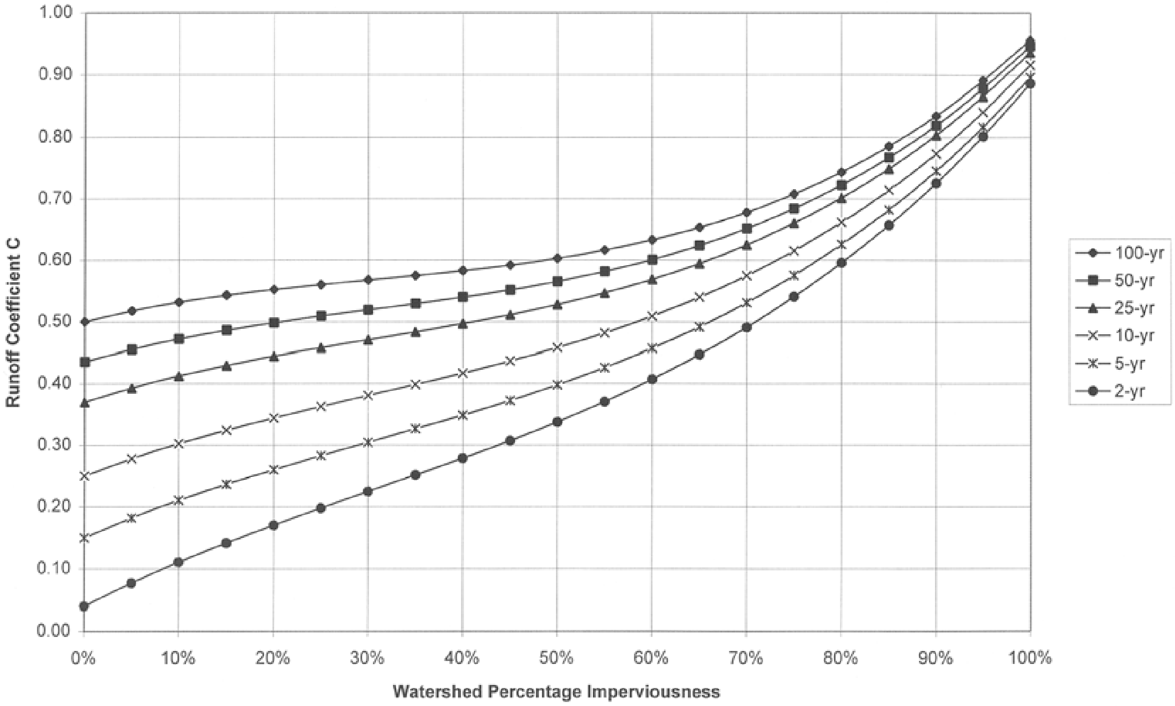


Figure 3.4 – Runoff Coefficients for NRCS Hydrologic Soil Groups C and D

3.4.3 Time of Concentration

The design rainfall duration used in the Rational Method is set to be the flow time required for runoff to flow through the longest waterway (starting at the most hydraulically distant point) within the watershed. This flow time is termed *the time of concentration* of the watershed. The longest waterway starts from the most upstream boundary of the watershed to the outlet or design point. A waterway can be divided into reaches: the *overland flow reach*, and any number of *channel flow reaches*. The time of concentration of the watershed is the cumulative flow times through the reaches.

3.4.3.1 Overland Flow Time

The water velocity of overland flow is a function of watershed slope and waterway roughness. There are many empirical formulas developed for estimating the overland flow time. For an urban setting, the Airport formula is recommended for the calculation of overland flow time as (McCuen et al 1984):

$$T_o = \frac{0.395(1.1 - C_5)\sqrt{L_o}}{S_o^{\ 0.33}} \qquad \textbf{(Equation 3-4)}$$

in which,

T_o = overland flow time in minutes,

L_o = overland flow length in feet,

S_o = overland slope in ft/ft, and

C_5 = 5-year runoff coefficient.

The maximum length for overland flow is up to 300 feet in a developed area and 500 feet in a rural area. Development is symbolized by street curbs, gutters and inlets. Under a rural condition, stormwater flows through natural depressions, turf strips and grass swales that significantly slow down the flow. As a result, the overland flow time in a rural area is longer.

3.4.3.2 Channel Flow Time

Channel flow time (or concentrated flow time) is the travel time in any defined form such as swales, gutters, channels, or the storm sewer. Channel flow time should be calculated separately for each reach that demonstrates different hydraulic properties such as slopes or material lining. The *SCS upland method* was developed to estimate the flow time through shallow swale flows. It is based on flow velocity through a swale.

$$T_f = \frac{L_f}{60V_f} \quad \textbf{where} \quad V_f = K\sqrt{S_f} \quad \textbf{or} \quad T_f = \frac{L_f}{60 * K\sqrt{S_f}} \qquad \textbf{(Equation 3-5)}$$

in which,

T_f = flow time in minutes,

L_f = flow length in feet,

V_f = flow velocity in feet/second,

S_f = reach slope in ft/ft, and

K = conveyance coefficient as described in **Table 3.3** (Guo 2006).

Table 3.3 Conveyance Coefficients for SCS Upland Method

Linings for Conveyance	Conveyance Coefficient
Meadow (rough bushes)	2.5
Tillage (crop fields, mountain vegetation)	4.5
Lawn (turf strip, gravel pavement)	7.0
Bare Soils (unlined ditches)	10.0
Grass Lined Swale (grass ditches)	15.0
Paved Water Way (street gutters)	20.0

3.4.3.3 Time of Concentration

The **computed time of concentration, T_c,** is the sum of the overland and channel flow times.

$$T_c = T_o + T_f \qquad \textbf{(Equation 3-6)}$$

The computed time of concentration is sensitive to the overland flow length. To be conservative, the time of concentration to be used in design in the City of Aspen is set to be the smaller between the computed and regional times of concentration. The **regional formula for time of concentration** is (UDFCD 2001, CCHCDDM 1999):

$$T_R = 10 + \frac{L}{180} \qquad \textbf{(Equation 3.7)}$$

in which T_R = regional time of concentration in minutes, and L = total waterway length in feet.

In no case should a Tc be less than 5 minutes in the City of Aspen. If the computed or regional time of concentration calculations indicate a lesser time, use 5 minutes instead.

For a small urban lot in the City of Aspen, the time of concentration is mainly dominated by the overland flow. For convenience, **Figure 3.5** is the plot to estimate the overland flow time using Equation 3-6 with C_5 =0.88 for paved flow path. Note that the minimum time of concentration for use in Aspen is 5 minutes.

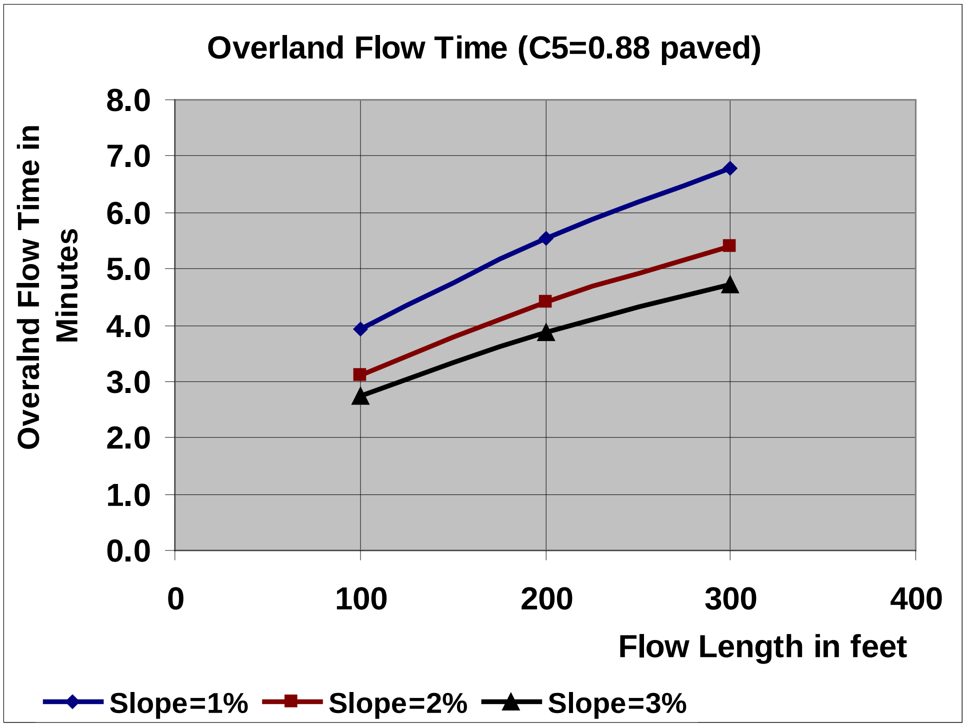


Figure 3.5 Approximate Overland Flow Times for Small Lots

3.4.4 Example Using Rational Method

A city block located in the City of Aspen is being redeveloped. The lot size is 350 ft by 500 ft. The land use proposed for this lot consists is 20% commercial at street corners and 80% of the lot is proposed to be single family residences. The ground elevations at four corners of this lot are marked in **Figure 3.6**. The project needs to determine the 10-year peak discharge released to the inlet.

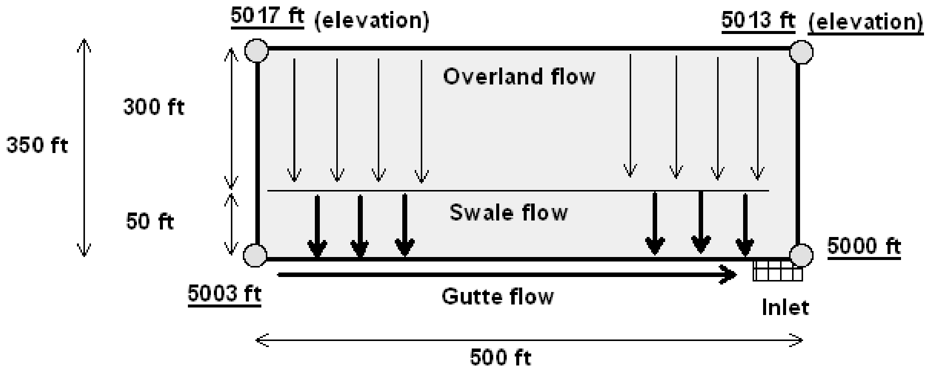


Figure 3.6 Example Watershed for Peak Flow Calculation

Solution:

Using hydrologic soil group B and an imperviousness of 70%, the runoff coefficient for this subdivision is:

$C_{10} = 0.54$

In order to calculate the overland flow time, the required 5-yr runoff coefficient is computed as:

$C_5 = 0.49$

The slope for the overland flow is calculated as:

$$S_o = \frac{5017 - 5003}{350} = 0.04$$

The overland flow time is calculated for the urban maximum allowable length of 300 ft using C_5=0.49 as:

$$T_o = \frac{0.393(1.1 - 0.49)\sqrt{300}}{0.04^{0.33}} = 12.0 \text{ minutes}$$

Before the overland flow reaches the street gutter in this example, the flow time through the additional waterway length of 50 feet is calculated using, Equation 3-8, the SCS upland method with K = 20 because of the paved surface.

$$T_1 = \frac{50}{60 \times 20\sqrt{0.04}} = 0.21 \text{ minutes}$$

The slope for the flow line along the street gutter is calculated as:

$$S_2 = \frac{5003 - 5000}{500} = 0.006$$

The gutter flow time is calculated as:

$$T_2 = \frac{500}{60 \times 20\sqrt{0.006}} = 5.38 \text{ minutes}$$

The computed time of concentration is the sum of the flow times as:

T_c = 12.0 + 0.21 + 5.38 = 17.6 minutes

As a check, the regional flow time through this subdivision is:

$$T_R = \frac{350 + 500}{180} + 10 = 14.7 \text{ minutes}$$

Because 14.7 minutes is greater than the minimum 5 minutes, the accepted time of concentration for the project is:

$T_d = 14.7$ *minutes*

From **Chapter 2 Rainfall** of this manual, the 10-yr one-hr precipitation depth is P_1= 0.77 inches for the Aspen area. The 10-yr rainfall intensity, I_{10}, and peak runoff, Q_{10}, are calculated using Equations 2-1 and 3-1 respectively, as:

$$I_{10} = \frac{88.8 \times 0.77}{(10+14.7)^{1.052}} = 2.34\ inch/hr$$

$Q_{10} = 0.54 \times 2.34 \times (350 \times 500)/ 43560 = 5.08$ *cfs*

3.4.5 Design Flow for Multiple Sub-Areas

Hydrologic homogeneity is one of the basic assumptions for small watershed hydrology. If the land uses or soil types in a watershed vary from one area to another, then it is necessary to divide the watershed into sub-areas. Each sub-area should have its own outlet that is termed “node” or “design point”. All nodes shall then be connected together by swales, street gutters, sewers, or roadside ditches that are often referred to as “link”. A node-link schematic represents the flow connectivity through the watershed.

The flow process through multiple subareas starts from the most upstream subarea to accumulate the flow time through the drainage network. At the n-th node on the waterway, the accumulated contributing area is:

$$(A_e)_n = C_n A_n + \sum_{i=1}^{i=n-1} C_i A_i \qquad \textbf{(Equation 3.8)}$$

The accumulated travel time through the drainage network is:

$$(T_c)_n = (T_c)_{n-1} + \frac{L_n}{60V_n} \qquad \textbf{(Equation 3.9)}$$

in which,

A_e = effective contributing area in acres,

T_c = accumulated time of concentration in minutes through the waterway system,

L = waterway length in feet,

V = flow velocity in feet/sec ,

i = i-th node upstream of the design point, and

n = n-th node at the design point.

When several links come to a node, the design rainfall duration or time of concentration at the node is the longest flow time among all incoming links. Knowing the contributing area and flow time, the peak discharge can be predicted by the Rational Method.

Example: Calculating Design Flow Through Multiple Subareas
As illustrated in **Figure 3.7**, the watershed is divided into three subareas. The sewer system is designed to pass the 10-year peak flow. The watershed parameters for these three subareas are summarized in **Table 3.4**. Determine the 10-year peak discharge at Point B.

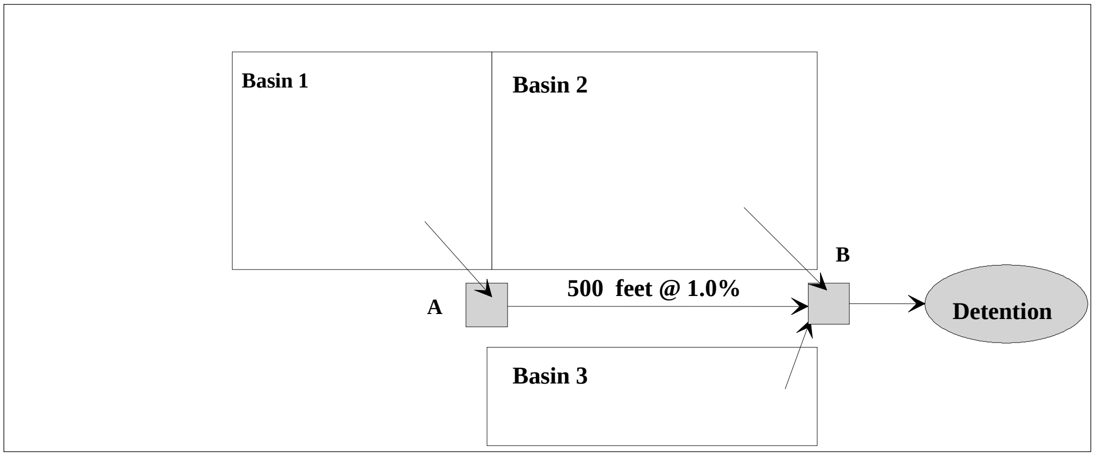


Figure 3.7 Layout for Multiple Subareas

Table 3.4 Parameters for Multiple Subareas

Subarea	Area (acres)	C	Tc (min)
1	2	0.55	15
2	5	0.65	22
3	1.5	0.81	12

Figure 3.7 indicates that there are three flow paths to reach Point B. Their flow times are:

From Basin 2: T_2 = 22 minutes
From Basin 3: T_3 = 12 minutes
From Basin 1: The flow time shall count for the time of concentration of Basin 1, and the flow time from Point A to B through the street.

According to the SCS upland method, the conveyance parameter for the paved gutter flow is 20.0 on a slope of 0.01. Using Equation 3-5, the flow time from Subarea 1 to Point B is the sum of the time of concentration of Subarea 1 plus the flow time through the 500-ft gutter as:

$$T_1 = 15 + \frac{500}{60 \times 20\sqrt{0.01}} = 19.17 \text{ minutes}$$

At Point B, the design rainfall duration (time of concentration) is the longest one among three incoming flow paths as:

$T_d = \max(T_1, T_2, T_3) = \max(19.17, 22, 12) = 22$ minutes.

The 10-year design rainfall intensity for this case is computed using Equation 2-1 as:

$$I_{10} = \frac{88.8 \times 0.77}{(10+22)^{1.052}} = 1.78\, inch/hr$$

$I = \frac{29 \times 1.2}{(10+22)^{0.789}} = 2.26$ inch/hr

According to Equation 3-18, the effective area, CA product, at Point B is calculated as:

$A_e = 0.81 \times 1.50 + (0.55 \times 2.0 + 0.65 \times 5.0) = 5.7$ *acres*

As a result, the 10-year peak discharge is calculated using Equation 3-1 as:

$Q = 2.26 \times 5.7 = 12.6$

Q= 1.78 x 5.7 = 10.17 cfs

3.4.6 Excel-based Computer Model – RATIONAL

RATIONAL is an excel-based computer model developed for the procedure described in this manual. The program, RATIONAL, is available from the website of the City of Aspen. RATIONAL is featured with the capabilities of computing the average runoff coefficient using the area-weighted method, time of concentration for multiple reaches, design rainfall intensity and peak flow using the Rational Method (Guo, Urbonas, MacKenzie, and Lloyd 2007).

3.5 CUHP for Rainfall-Runoff Simulation

3.5.1 Background

The Colorado Urban Hydrograph Procedure (CUHP) is a synthetic unit hydrograph method that was developed and calibrated by the rainfall-runoff data collected from the Denver and Boulder metropolitan areas in Colorado. CUHP has been supported and accepted as the official flood prediction method by the UDFCD in Denver Colorado. CUHP2005 is an excel-based computer program that provides numerical automation using CUHP to generate hydrographs at design points. These computed hydrographs can be saved into a text file that can be imported into EPA SWMM Version 5 (SWMM5) for channel and reservoir routing. Both CUHP2005 and SWMM5 computer models have been widely accepted and applied to stormwater simulation studies in the State of Colorado. On-line documentation is available for both models as follows:

- **hthttp://www.udfcd.org/downloads/down_disclaimer.htm**

http://www2.epa.gov/water-research/storm-water-management-model-swmm These models are free and can be downloaded at the web addresses above. Because both of these models are well documented with complete user manuals, this chapter will only focus on model inputs for applications in the City of Aspen rather than the equations and numerical methods used in the models.

3.5.2 CUHP Input Parameters

CUHP is an empirical procedure to predict runoff hydrographs using the synthetic unit hydrograph method (Snyder 1938, Sherman 1932). A CUHP2005 computer model is composed of rainfall data, sub-area hydrologic parameters, and options for various printout format, and user-defined practices. Details are discussed as follows:

3.5.2.1 Design Rainfall

CUHP requires the input of a design rainfall distribution expressed as incremental rainfall depths in inches with a pre-selected time interval such as 1, 5, 10, or 15 minutes. All the 2-hr design rainfall curves discussed in Chapter 2 – Rainfall can be generated by CUHP2005 using the one-hr rainfall depth. Of course, the user has the option to enter an observed rainfall distribution with duration up to 6 hours or 72 time steps with a time interval of 5 minutes. For most urban studies, the rainfall duration for the unit hydrograph should be 5 minutes. However, such duration may be increased to 10 or 15 minutes for larger watersheds or decreased to one (1) minute for smaller watersheds.

3.5.2.2 Watershed Input Parameters

CUHP can accept as many watersheds in one computer run as the user wishes. A large watershed should be divided into smaller watersheds between 100 to 150 acres in size. As a rule of thumb, the watershed length to width ratio shall not exceed 4:1. For each watershed, the following input data needs to be entered:

<u>Horton's Infiltration Rates</u> (see **Table 3.1**)

<u>Pervious and Impervious Depression</u> in inches (see **Table 3.2**)

<u>Watershed area</u> (square miles)— the tributary area is used to generate runoff hydrograph.

<u>Length of Waterway</u> (miles)—the length of waterway should be the longest flow path from the most upstream boundary to the outlet point. It shall be measured by following the waterway meandering pattern.

<u>Length to Centroid</u> (miles)—the centroid of a watershed is the geometric center that can be measured based on the area's shape and size. Projecting the area-centroid laterally onto the waterway locates the waterway centroid. From the waterway centroid to the outlet gives the length to centroid.

<u>Percent Impervious</u> (%)—the portion of the watershed's surface area that is impervious or paved. Percent impervious is expressed as a percent value between 0 and 100.

<u>Waterway Slope in ft/ft</u> -- Waterway slope is an important and sensitive factor when calculating the time parameters used in CUHP. A waterway shall be divided into several reaches, according to the uniformity of the invert slope that is calculated as:

$$S_i = \frac{H_i}{L_i}$$

(Equation CUHP-1)

in which S_i = slope for i-th reach, H_i = vertical drop in elevation, and L_i = length of reach. Equation CUHP-1 shall be applied to all reaches in order to produce the length-weighted slope as:

$$S_0 = \left[\frac{1}{L}\sum_{i=1}^{i=n}\left(L_i S_i^{\,0.24}\right)\right]^{4.17}$$

(Equation CUHP-2)

in which S_o = waterway representative slope in ft/ft, and L = total length of waterway. Equation CUHP-2 is operated with topographic maps that do not reveal the drops and lining roughness through the waterway. As recommended in **Figure 3.8**, when the measured slope is steeper than 4%, it is subject to a correction. For instance, 5.7% shall be entered into CUHP for the measured slope of 8%, according to **Figure 3.8**.

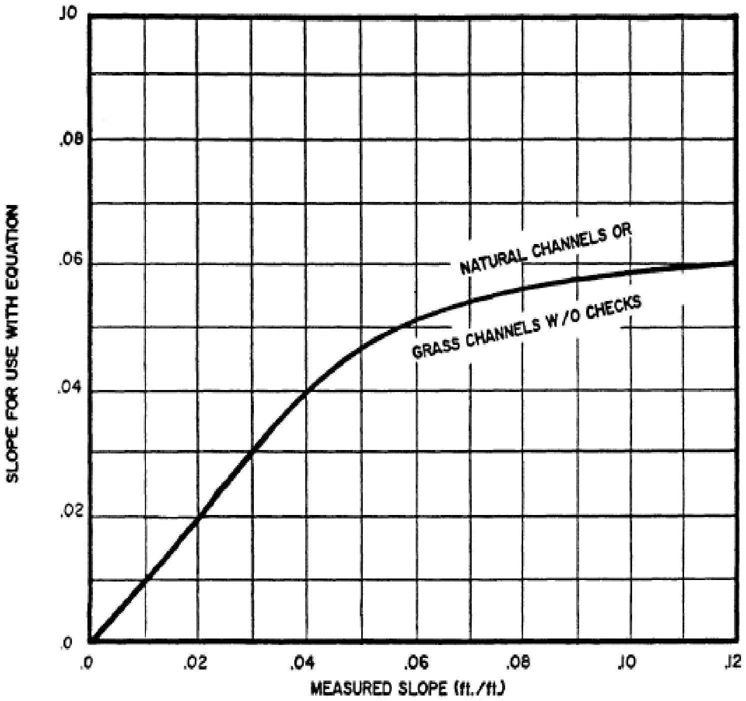


Figure 3.8 Corrections on Measured Waterway Slope

3.5.2.3 User Option to Reshape Unit Graph

The program, CUHP2005, computes the time to peak coefficient, C_t , and peak parameter, C_p, according to the watershed area and imperviousness percentage. However, the user has an option of overriding the computed values for these parameters. The shape 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 time-width at 50% of peak being ahead of the time to peak and 0.45 of the time-width at 75% of peak being ahead of the time to peak. If the user has derived unit hydrographs from other sources, CUHP allows the user to reshape the unit hydrograph according to the user-defined time-widths.

3.5.2.4 User Option to Define Cascading Flows for Low Impact Layout

The CUHP2005 computer model recognizes the effects of cascading flows in which the unconnected impervious areas drains onto porous area for additional infiltration effects. With the concept of cascading flow, a typical urban watershed, as shown in **Figure 3.9** may have four separate surface runoff components as:

1. Impervious area directly connected to the drainage system (DCIA).
2. Impervious area that drains onto or across pervious surfaces (UIA).
3. The pervious area receiving runoff from impervious portions (RPA).
4. The separate pervious area (SPA) not receiving runoff from impervious surfaces.

For modeling convenience, two design variables are defined as:

$$D = \frac{DCIA}{IA}$$ **(Equation CUHP-3)**

$$R = \frac{RPA}{PA}$$ **(Equation CUHP-4)**

IA = total impervious area, DCIA = directly (hydraulically) connected impervious area, D= fraction of the total impervious area directly connected to the drainage system, RPA = receiving pervious area, PA = total pervious area, R = fraction of pervious area receiving disconnected impervious runoff, SPA = separate pervious area, and UIA = unconnected impervious area.

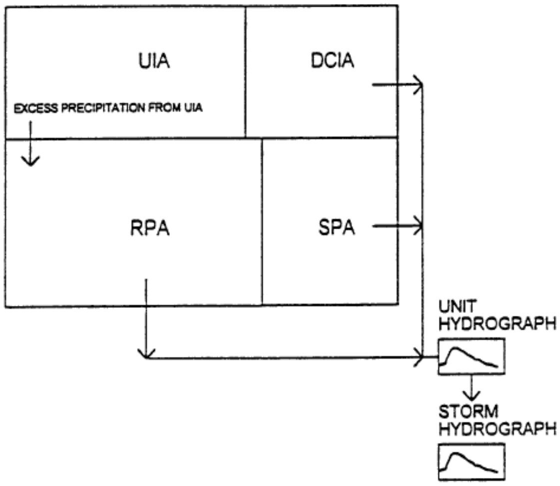


Figure 3.9 Illustration of Cascading Flow Layout

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

- DCIA (directly connected impervious area) is the input variable that specifies the on-site drainage pattern. Option 1 represents the Standard Management Practice (SMP) in which the impervious and pervious areas are independently, separately drained onto the street. Option 2 represents the Best Management Practice (BMP) in which the impervious area drains onto porous area before the street.

- D is the variable to define the fraction of the total impervious area directly connected to the drainage system. It ranges from 0.01 to 1.0.

- R is the variable to define the fraction of total pervious area receiving runoff from the disconnected impervious areas. It ranges from 0.01 to 1.0.

Although CUHP provides the default values for R and D used in SMP and BMP, the user has the option of replacing the default with the user-defined values.

3.5.3 File Management

CUHP2005 provides three options to structure the printout in a spreadsheet format, including summary for watersheds, unit hydrographs, and storm hydrographs respectively. CUHP2005 is a hydrograph generator that does not have any hydrologic routing capability. The user has options to save all the predicted hydrographs in a text file and then transfer this file into the EPA SWMM5 computer model as an input file for various hydrologic routing features. Details can be found in CUHP2005 user manual.

3.6 EPA SWMM for Rainfall-Snowmelt Runoff Simulation

3.6.1 Background

SWMM was first developed in 1971 and has undergone several major upgrades since then. The current edition, EPA Storm Water Management Model-Version 5 (SWMM5), is a complete re-write of the previous release. Running under Windows, SWMM5 provides an integrated environment for editing study area input data; running hydrologic, hydraulic and water quality simulations; and viewing the results in a variety of formats (Rossman 2005). These include color-coded drainage area and conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses.

As stated in the user manual, SWMM5 is a dynamic rainfall-runoff simulation model used for single event or long-term simulation of rainfall and snowmelt runoff for both quality and quantity studies. The runoff component of SWMM5 operates on a watershed area that receives precipitation and generates runoff and pollutant loads. The routing portion of SWMM5 transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM5 tracks the quantity and quality of runoff generated within each watershed, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.

3.6.2. SWMM Input Parameters

A SWMM5 computer model consists of four basic components: (1) Time Variables, (2) Climatology Parameters, (3) Watershed Parameter, and (4) Network for Hydrologic Routing. SWMM accepts interface files to transfer pre-processed rainfall or runoff data sets into a SWMM computer model to speed up simulations. For instance, the option of Rainfall Interface File is used to load a long term rainfall or snowfall record into the SWMM computer model for simulation studies.

It is important to understand that a CUHP/SWMM in-tandem model does not need Climatology and Watershed Parameters in the SWMM model because the pre-processed CUHP hydrographs can be directly transferred into the SWMM model for Hydrologic Routing. Details of interface files (Option of Inflow) can be found in SWMM User Manual (Rossman, 2005).

3.6.2.1 Time Variable

SWMM follows the clock time to conduct rainfall and runoff analyses. The user must specify the beginning and the end of the storm event and the time steps used for computation and reporting.

3.6.2.2 Climatology (Not needed if CUHP is used.)

<u>Rain Gage</u> is the object for the user to define the design rainfall distribution that can be expressed in incremental volume or intensity for each time step.

<u>Air Temperature</u> is used when simulating snowfall and snowmelt processes during runoff calculations. For rainfall and runoff simulations, temperature data are not required.

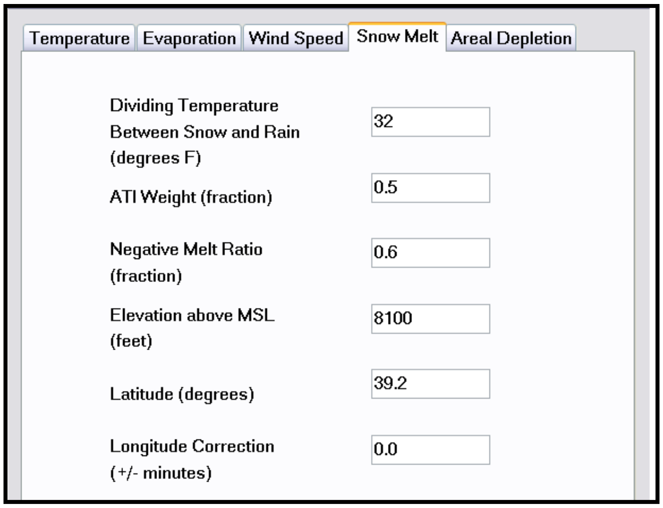
Evaporation can occur to standing water on watershed surfaces, for subsurface water in groundwater aquifers, and for water held in storage units such as detention basins. Evaporation rates can be prescribed as a single constant value, a set of monthly average values as shown in **Table 3.5**, or a user-defined time series of daily values.

Table 3.5 Monthly Evaporation Rates inch/day
(Observed in Chatfield Reservoir, Denver, Colorado)

Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
0.04	0.04	0.06	0.12	0.2	0.28	0.30	0.30	0.25	0.16	0.08	0.04

Wind Speed is an optional climatic variable that is only used for snowmelt calculations. SWMM can use either a set of monthly average wind speeds or wind speed data contained in the same climate file used for daily minimum/maximum temperatures.

Snowmelt Parameters are climatic variables that apply across the entire study area when simulating snowfall and snowmelt. They include: (a) the air temperature, such as 32F^o, at which precipitation falls as snow (b) heat exchange properties of the snow such as antecedent temperature Index (ATI) and negative melt ratio, and (c) surface study area elevation, latitude, and longitude correction. **Figure 3.10** is the summary of the recommended values for snowmelt studies for the Aspen area.



Dividing Temperature Between Snow and Rain (degrees F): 32
ATI Weight (fraction): 0.5
Negative Melt Ratio (fraction): 0.6
Elevation above MSL (feet): 8100
Latitude (degrees): 39.2
Longitude Correction (+/- minutes): 0.0

Figure 3.10 Recommended Values for Design Variables used Snowmelt Studies

Areal Depletion refers to the tendency of accumulated snow to melt non-uniformly over the surface of a watershed. As the melting process proceeds, the area covered by snow gets reduced. This behavior is described by an Areal Depletion Curve that plots the fraction of total area that remains snow covered against the ratio of the actual snow depth to the depth at which there is 100% snow cover.

Snow Pack Parameters characterize the buildup, removal, and melting of snow over three types of storage areas within a watershed, including (a) the plowable snow pack area as a user-defined fraction of the total impervious area, (b) the impervious snow pack area covers the remaining impervious area of a watershed, and (c) the pervious snow pack area encompasses the entire pervious area of a watershed.

3.6.2.3 Watershed Input Parameters (Not needed if CUHP is used.)

Based on the land uses and types of soils, a watershed is divided into smaller subareas for stormwater analyses. Among these subareas, the hydrographs are routed and combined along the drainage network. For each subarea, the following input data need to be entered.

Subarea (in acres) is the tributary area used to generate runoff hydrograph and pollutant loadings.

Width of Subarea (in feet) is referred to the collector channel across the KW plane. As a rule of thumb, the width of the KW plane is approximated to be twice the length of the waterway (Guo and Urbonas 2009).

Subarea Slope (in percent) represents the average slope on the KW plane. The transverse slope of the watershed is a good approximation (Guo 1998).

Percent Impervious represents the imperviousness percentage of the subarea between 0 and 100.

Manning's N's for pervious and impervious surfaces are used to calculate flood wave movement. Overland flow is a two-dimensional sheet flow that is significantly affected by the surface resistance. As recommended, the value of 0.25 is used for pervious surface, and 0.025 is for impervious surface.

Pervious and Impervious Depression in inch (see **Table 3.2**)

Percent of Zero-Imperv is the variable that represents the percent of impervious area with no depression storage such as roof area in a subarea. A value of 25% is recommended.

Subarea Routing represents the arrangement of cascading flows on the KW plane. IMPERV means the upper porous area draining onto the lower impervious area. PERV is the option to drain the upper impervious area onto the lower porous area, and OUTLET implies that the pervious and impervious areas are separately drained or no cascading flow at all.

Percent Routed is the variable that quantifies the percent of the upper area draining onto the lower area when cascading inlet option is selected.

Soil Loss Parameters are user-defined infiltrating rates used in Horton's formula (see **Table 3.3**)

Downstream Junction Node is the object to represent the location where the hydrograph generated from a subarea is placed. Between two junction nodes is a channel or a pond. A node (similar to a manhole) is described by its invert elevation and the maximum and initial water depths if the node is surcharged. In case of flooding, the user can specify the ponded area in sq feet atop the junction.

3.6.3 Drainage Network for Hydrologic Routing

Hydrologic routing schemes are numerical methods to transport hydrographs through a channel or a reservoir by solving the equation of continuity. A kinematic wave (KW) routing method ignores the backwater effect while a dynamic wave (DW) routing method takes into consideration the flow acceleration and the storage effects under the backwater profiles. In comparison, DW calculations are sensitive to the time increment. The rule of thumb is to select a short time step such as 1 to 60 seconds for DW calculations and 300 seconds or longer for KW calculations. To be conservative, the KW model is recommended for stormwater planning studies while the DW model can be accepted for on-site stormwater designs and detailed studies.

Hydrologic routing schemes in SWMM5 are classified into conveyance routing, flow diversion, and detention basin routing.

3.6.3.1 Conveyance Flow Routing for Channels and Pipes

In an urban area, flows are collected and conveyed by streets, sewers, roadside ditches, and channels. As illustrated in **Figure 3.9**, these conveyance facilities are modeled as:

Case 1: Street and Sewer Section representing a street with an underground sewer,
Case 2: Culvert and Overtopping Flow representing a crossing culvert underneath a roadway

Case 3: Street and Roadside Ditch representing a street with a swale ditch
Case 4: Overbank Channel representing a composite channel with low and high flow sections.

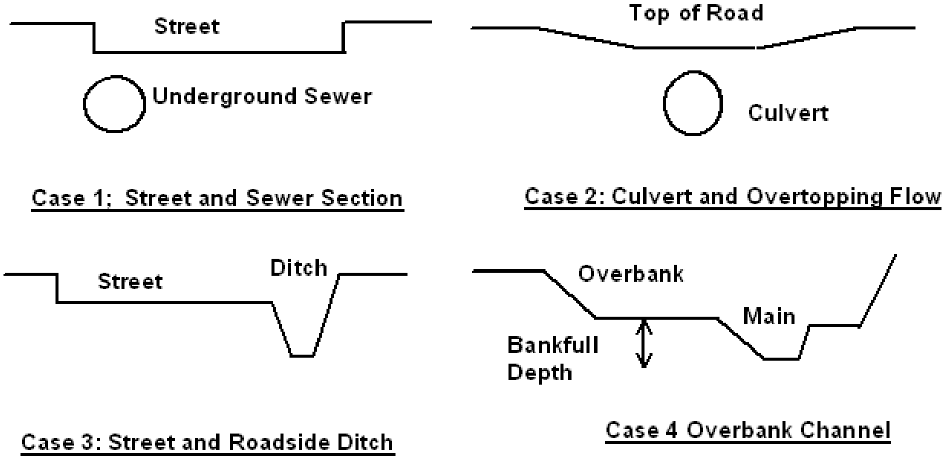


Figure 3.11 Conveyance Facilities in Urban Area

A conveyance facility is described by its upstream and downstream nodes, offset distances from the upstream and downstream node inverts, length, cross sectional geometry, hydraulic parameters, bankfull depth, and minor loss coefficients. Computationally, the KW routing through a composite section begins with the low flow section such as the pipe or roadside ditch. After the low flow section is filled up to its bankfull depth, the excess water begins to spill into the overbank section or street section.

3.6.3.2 Reservoir Flow Routing for Detention Basins

Detention basin is a hydraulic structure designed for flood control. Numerically, a detention system is modeled as a conveyance element with a large storage volume. According to the basin geometry and outlet work, a detention system can be described by its stage-area curve with a set of orifices and weirs for initial planning studies or a stage-outflow curve for the final design.

In practice, roadway embankments and culvert entrance can form storage volumes. It is important to understand that these local, random storage volumes are not reliably maintained for flood control purposes. During a major event, the embankment could be washed away. Therefore, it is suggested that any and all non-institutionalized storage volumes in the watershed be excluded for the flood control studies, but can be included in the computer model when investigating the existing flooding condition such as forensic studies.

3.6.3.3 Flow Diversion Routing

Diversion of storm runoff occurs when storm runoff is transferred across the physical boundary of a watershed. In an urban area, a flow diversion is often caused by street intersections or drainage structures. To model a flow diversion, the relationship of inflow, Q, versus diverted flow, Q_2, must be developed from the configuration of the diversion structure.

Example for Flow Intercepted by Street Inlet
As illustrated in **Figure 3.10**, a 36-inch storm sewer In the City of Aspen is designed to intercept the 10-year peak discharge of 40 cfs from the street inlet. The 100-yr peak discharge at the street inlet is 130 cfs. To model the 100-year event on this street, the street inlet is assumed to be capable of intercepting

the 100-yr flood flow up to 40 cfs. The street flow immediately downstream of the inlet is the difference between the 10- and 100-year runoff flows.

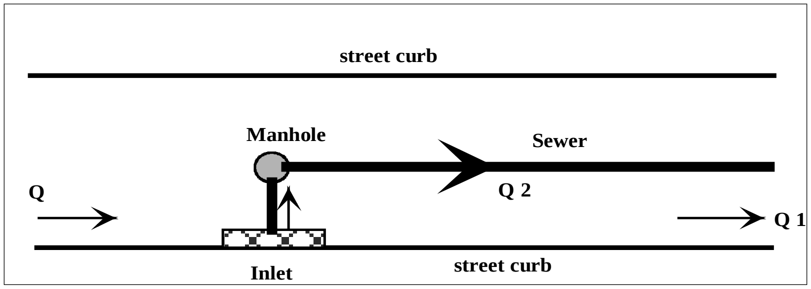


Figure 3.12 Interception of Street Inlet

For this case, the flow diversion table used in the SWMM5 computer model shall follow the inflow rising hydrograph to the 10-year peak discharge and leveled off as shown in **Table 3.6.**

Table 3.6 Flow Diversion at Street Inlet

Q-100 yr (inflow rate) cfs	0	40	41	130
Q-10 yr (diverted flow) cfs	0	40	40	40

3.7 References

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