

CHAPTER 2

HYDROLOGY

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Chapter Two – Hydrology

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2.1 Overview

2.1.1 Introduction

Estimation of the peak rate of runoff, volume of runoff, and time distribution of flow is fundamental to the design of drainage facilities. Errors in the estimation will result in a structure that is either undersized and causes drainage problems (e.g., flooding, safety, nuisance, etc.) or oversized and costs more than necessary. Any hydrologic analysis is only an approximation. The relationship between the amount of precipitation on a drainage basin and the amount of runoff from the basin is complex and there are no exact solutions.

2.1.2 Factors Affecting Floods

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

Drainage Basin Characteristics

Size and Shape, Slope, Ground Cover and Land Use, Geology, Soil Types, Surface Infiltration, Ponding and Storage, Watershed Development Potential

Stream Channel Characteristics

Geometry and Configuration, Natural Controls, Artificial Controls, Channel Modifications, Aggradation, Degradation, Debris, Mannings n, Slope

Floodplain Characteristics

Slope, Vegetation, Alignment, Storage, Location of Structures, Obstructions of Flow

Meteorological Characteristics

Time Rate and Amounts of Precipitation, Historical Flood Events

Table 2-1 Recommended Hydrologic Methods

<u>Method</u>	<u>Size Limitations¹</u>	<u>Comments</u>
Rational	0 - 150 Acres	Method can be used for estimating peak flows and the design of small subdivision-type storm drain systems. (Method shall not be used for design of storage facilities.)
SCS ²	0 - 2,000 ³ Acres	Method can be used for estimating peak flows and hydrographs.
Curve Number		Method shall be used for the design of all drainage structures and shall be used for design of any storage facility or any other facility with a drainage basin greater than 150 acres.

The Lincoln Public Works and Utilities Department has selected the HEC-HMS computer program for stormwater master planning efforts and recommends that this program be used for stormwater system design

¹Size limitation refers to the subwatershed size to the point where the stormwater management facility (i.e., culvert, inlet) is located.

²SCS is the Soil Conservation Service Method. Although the SCS is now called the Natural Resources Conservation Service, the hydrologic method is still called SCS.

³ Will likely be less than 2000 acres in urban areas due to the need for homogeneous subwatersheds.

2.1.3 Hydrologic Method Selection

Many hydrologic methods have been developed and used in urban watersheds. Table 2-1 lists two recommended methods. Other methods may be used if they receive prior approval from the Director of Public Works and Utility and if they are calibrated to local conditions and tested for accuracy and reliability. In addition, complete source documentation must be submitted for approval.

Methods listed in Table 2-1 have been selected for use in Lincoln, Nebraska based on several considerations, including the following:

- Verification of their accuracy in duplicating local hydrologic estimates of a range of design storms.
- Availability of equations, nomographs, and computer programs.
- Use and familiarity with the methods used by local municipalities and consulting engineers.

2.2 Symbols and Definitions

To provide consistency within this chapter, as well as throughout this manual, the following symbols will be used. These symbols were selected because of their wide use in hydrologic publications.

Table 2-2 Symbols and Definitions

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
A	Drainage area	acres or mi ²
C	Runoff coefficient	-
C _f	Frequency factor	-
CN	SCS-runoff curve number	-
d	Time interval	hours
F	Pond and swamp adjustment factor	-
I	Rainfall intensity	in./hr
IA	Percentage of impervious area	%
I _a	Initial abstraction from total rainfall	in.
NRCS	Natural Resources Conservation Service	-
n	Manning's roughness coefficient	-
P	Accumulated rainfall	in.
Q	Rate of runoff	cfs
q	Storm runoff during a time interval	in.
R	Hydraulic radius	ft
S or Y	Ground slope	ft/ft or %
S	Potential maximum retention storage	in.
SCS	Soil Conservation Service	-
SL	Main channel slope	ft/ft
S _L	Standard deviation of the logarithms of the peak annual floods	-
T _B	Time base of unit hydrograph	hours
t _c or T _c	Time of concentration	min or hours
T _L	Lag time	hours
V	Velocity	ft/s

2.3 Design Frequency

2.3.1 Overview

Since it is not economically feasible to design a structure for the maximum runoff a watershed is capable of producing, a design frequency must be established. The designer should note that the 5-year flood is not one that will necessarily be equaled or exceeded every five years. There is a 20 percent chance that the flood will be equaled or exceeded in any year; therefore, the 5-year flood could conceivably occur in several consecutive years. The same reasoning applies to floods with other return periods.

2.3.2 Frequency Design Criteria

Cross Drainage: Cross drainage facilities transport storm runoff under roadways. The cross drainage facilities shall be designed to convey (at a minimum) the 50-year runoff event without overtopping the roadway. The flow rate shall be based on upstream ultimate buildout land-use conditions. In addition, the 100-year frequency storm shall be routed through all culverts to be sure structures are not flooded or increased damage does not occur to the roadway or adjacent property for this design event.

Storm drains: A storm drain shall be designed to accommodate a 5-year storm in residential areas and a 10-year storm in commercial developments, downtown areas and in industrial developments. The design shall be such that the storm runoff does not: increase the flood hazard significantly on adjacent property; encroach onto the street or highway so as to cause a safety hazard by impeding traffic, emerging vehicles, or pedestrian movements to an unreasonable extent. A residential area downstream of a commercial, downtown or industrial development shall be designed to a 10-year storm event.

Based on these criteria, a design involving temporary street or road inundation is acceptable practice for flood events greater than the design event but not for floods that are equal to or less than the design event. Thus, if a storm drainage system crosses under a roadway, the design flood must be routed through the system to show that the roadway will not be overtopped by this event. The excess storm runoff from events larger than the design storm may be allowed to inundate the roadway or may be stored in areas other than on the roadway until the drainage system can accommodate the additional runoff.

Inlets: Inlets shall be designed for a 5-year storm in residential areas and small commercial developments and a 10-year storm in downtown areas industrial developments, and arterial roads.

Detention and retention storage facilities: All storage facilities shall be designed to provide sufficient storage and release rates to accommodate the 2-, 10-, and 100-year design storm events such that the post-development peak discharges do not exceed the pre-development rates. The design shall be such that the storm runoff does not increase the flood hazard significantly for adjacent, upstream, or downstream property or cause safety hazards associated with the facility. An emergency spillway shall be provided. For storage facilities, outlet designs that provide some control for flood events below the 2-year storm (e.g., v-notch weirs) are preferred over outlets that do not provide this control (e.g., pipes). In addition, the final design shall be checked to ensure that flood peaks at the downstream property line have not increased. If a detention or retention facility is designed in combination with a Stormwater quality facility, the combined facility will be designed to meet both facilities criteria.

Stormwater Quality: All Stormwater quality facilities shall be designed to detain the 70th and 80th percentile rainfall events measured at every discharge point from the project area.

2.3 Rational Method

2.4.1 Introduction

The rational method can be used to estimate the design peak discharge for areas as large as 150 acres. This method, while first introduced in 1889, is still used in many engineering offices in the United States. Even though it has frequently come under criticism for its simplistic approach, no other drainage design method has received such widespread use.

2.4.2 Concept and Equation

The rational formula estimates the peak rate of runoff at any location in a watershed as a function of the drainage area, runoff coefficient, and mean rainfall intensity for a duration equal to the time of concentration (the time required for water to flow from the hydraulically most remote point of the basin to the location being analyzed). The rational formula is expressed as follows:

$$Q = CIA \quad (2.1)$$

Where:

Q = peak rate of runoff, cfs

C = runoff coefficient representing a ratio of runoff to rainfall for future land-use conditions

I = average rainfall intensity for a duration equal to the time of concentration, for a selected return period in./hr.

A = drainage area tributary to the design location, acres

2.4.3 Application

Peak discharges estimated using the rational formula are very sensitive to the parameters that are used. The designer must use good engineering judgment in assigning values to these parameters. Each of the parameters used in the rational method are discussed below.

2.4.3.1 Time of Concentration

The time of concentration (t_c) is the time required for water to flow from the hydraulically most remote point of the drainage area to the point under investigation. Use of the rational formula requires the time of concentration (t_c) for each design point within the drainage basin. The duration of rainfall is then set equal to the time of concentration and is used to estimate the rainfall intensity (I). For a storm drain system, the time of concentration consists of an inlet time plus the time of flow in a closed conduit or open channel to the design point. Inlet time is the time required for runoff to flow over the surface to the nearest inlet and is primarily a function of the length of overland flow, the slope of the land and surface cover. Pipe or open channel flow time can be estimated from the hydraulic properties of the conduit or channel. For each drainage area, the distance is determined from the inlet to the most remote point in the tributary area. From a topographic map, the average slope is determined for the same distance.

To obtain the total time of concentration, the pipe or open channel flow time must be calculated and added to the inlet time. After first determining the average flow velocity in the pipe or channel, the travel time is obtained by dividing velocity into the pipe or channel length. Manning's equation can be used to determine velocity. See Chapter 5 - Open Channel Hydraulics - for a discussion of Manning's equation.

Time of concentration is an important variable in most hydrologic methods. Several methods are available for estimating t_c . Appendix 2-C (Travel Time Estimation) at the end of this chapter describes the method from the SCS Technical Release No. 55 (2nd Edition). For inlet design the minimum t_c recommended shall not be less than 8 minutes.

2.4.3.1.1 Common Errors

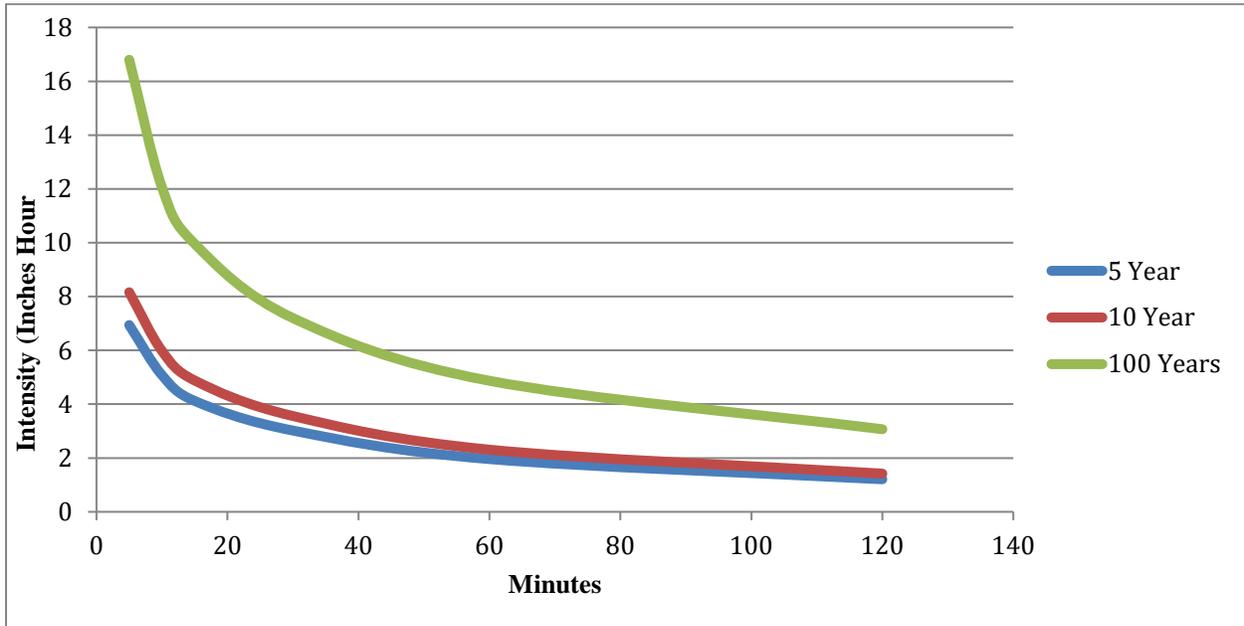
Two common errors should be avoided when calculating t_c . First, in some cases runoff from a portion of the drainage area which is highly impervious may result in a greater peak discharge than would occur if the entire area were considered. In these cases, adjustments can be made to the drainage area by disregarding those areas where flow time is too slow to add to the peak discharge. Sometimes it is necessary to estimate several different times of concentration to determine the design flow that is critical for a particular application.

Second, when designing a drainage system, the overland flow path is not necessarily perpendicular to the contours shown on available mapping. Often the land will be graded and swales will intercept the natural contour and conduct the water to the streets, which reduces the time of concentration. Sheet flow paths shall not be used in excess of 100 ft. in urban areas and 150 ft. in rural areas. Sheet flow conditions are not likely to be sustained for greater lengths and the estimated T_c will be too large. Exceptions to the above may be allowed on a case by case basis.

2.4.3.2 Rainfall Intensity

The rainfall intensity (I) is the average rainfall rate (in./hr.) for a duration equal to the time of concentration for a selected return period. Once a particular return period has been selected for design and a time of concentration calculated for the drainage area, the rainfall intensity can be determined from Intensity-Duration-Frequency (IDF) curves.

Figure 2-1 NOAA Atlas 14 IDF Curve Inches/Hour {based on tabular data, to be smoothed out via power function regression}



2.4.3.3 Runoff Coefficient

The runoff coefficient (C) is the variable of the rational method least susceptible to precise determination and requires judgment and understanding on the part of the designer. Engineering judgment will always be required in the selection of runoff coefficients since a typical coefficient represents the integrated effects of many drainage basin parameters. The following discussion considers only the effects of soil groups, land use and average land slope.

The method for determining the runoff coefficient (C) is based on land use, soil groups and land slope. Table 2-4 in Manual gives the recommended coefficient C of runoff for pervious surfaces by selected hydrologic soil groupings and slope ranges. *The value of C shall be based on fully built-out land use conditions. The minimum runoff coefficient shall be 0.4, unless owner can clearly demonstrate that the value less than 0.4 is adequate.*

Table 2-4 gives the recommended coefficient C of runoff for pervious surfaces by selected hydrologic soil groupings and slope ranges. From this table the C values for non-urban areas such as forest land, agricultural land, and open space can be determined. Soil properties influence the relationship between runoff and rainfall since soils have differing rates of infiltration. Infiltration is the movement of water through the soil surface into the soil. Based on infiltration rates, the Soil Conservation Service (SCS) has divided soils into four hydrologic soil groups as follows:

- Group A Soils having a low runoff potential due to high infiltration rates. These soils consist primarily of deep, well-drained sands and gravels.
- Group B Soils having a moderately low runoff potential due to moderate infiltration rates. These soils consist primarily of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.
- Group C Soils having a moderately high runoff potential due to slow infiltration rates. These soils consist primarily of soils in which a layer exists near the surface that impedes the downward movement of water or soils with moderately fine to fine texture.

Group D Soils having a high runoff potential due to very slow infiltration rates. These soils consist primarily of clays with high swelling potential, soils with permanently high water tables, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious parent material.

A list of soils for the City of Lincoln and their hydrologic classification is presented in the Lancaster County Soil Survey.

As the slope of the drainage basin increases, the selected C value should also increase. This is caused by the fact that as the slope of the drainage area increases, the velocity of overland and channel flow will increase, allowing less opportunity for water to infiltrate. Thus, more of the rainfall will become runoff from the drainage area.

It is often desirable to develop a composite runoff coefficient based on the percentage of different types of surface in the drainage area. Composites can be made with Tables 2-3 and 2-4. The composite procedure can be applied to an entire drainage area or to typical "sample" blocks as a guide to selection of reasonable values of the coefficient for an entire area.

Table 2-3 Recommended Coefficient of Runoff Values for Various Selected Land Uses

<u>Description of Area</u>	<u>Runoff Coefficients</u>
Business: Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential: Single-family areas	0.30-0.50
Multi units, detached	0.40-0.60
Multi units, attached	0.60-0.75
Suburban	0.25-0.40
Residential (1 acre lots or larger)	0.30-0.45
Apartment dwelling areas	0.50-0.70
Industrial: Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.40
Railroad yard areas	0.20-0.40
Unimproved areas	0.04-0.38 (see Table 2-4)

Source: Hydrology, Federal Highway Administration, HEC No. 19, 1984

Table 2-4 Recommended Coefficient of Runoff for Pervious Surfaces (Unimproved Areas) By Selected Hydrologic Soil Groupings and Slope Ranges

<u>Slope</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Flat (0 - 1%)	0.04-0.09	0.07-0.12	0.11-0.16	0.15-0.20
Average (2 - 6%)	0.09-0.14	0.12-0.17	0.16-0.21	0.20-0.25
Steep (Over 6%)	0.13-0.18	0.18-0.24	0.23-0.31	0.28-0.38

Source: Storm Drainage Design Manual, Erie and Niagara Counties Regional Planning Board.

2.4.3.3.1 Infrequent Storm

The coefficients given in Tables 2-3 and 2-4 are applicable for storms of 5-year to 10-year frequencies. Less frequent, higher intensity storms will require modification of the coefficient because infiltration and other losses have a proportionally smaller effect on runoff (Wright-McLaughlin, 1969). The adjustment of the rational method for use with major storms can be made by multiplying the right side of the rational formula by a frequency factor C_f . The rational formula now becomes:

$$Q=C_fCIA \tag{2.1}$$

C_f values are listed in Table 2-5. The product of C_f times C shall not exceed 1.0.

Table 2-5 Frequency Factors for Rational Formula

<u>Recurrence Interval (years)</u>	<u>C_f</u>
25	1.1
50	1.2
100	1.25

2.4.4 Limitations

Some precautions should be considered when applying the rational method.

- The first step in applying the rational method is to obtain a good topographic map and define the boundaries of the drainage area in question. A field inspection of the area should also be made to determine if the natural drainage divides have been altered.
- In determining the runoff coefficient (C) value for the drainage area, thought should be given to future changes in land use that might occur during the service life of the proposed facility that could result in an inadequate drainage system. Also, the effects of permanent upstream detention facilities may be taken into account.
- Restrictions to the natural flow such as highway crossings and dams that exist in the drainage area should be investigated to see how they affect the design flows. Don't include detention behind road crossings, as future improvements may negate such detention.
- The charts, graphs and tables included in this section are not intended to replace reasonable and prudent engineering judgment which should permeate each step in the design process.

The rational formula is best suited for small, highly impervious areas and least suitable for large drainage areas or drainage areas in natural or undeveloped conditions.

2.5 SCS Unit Hydrograph Method

2.5.1 Introduction

Techniques developed by the U. S. Soil Conservation Service for calculating rates of runoff require the same basic data as the rational method: drainage area, a runoff factor, time of concentration and rainfall. The SCS approach, however, is more sophisticated in that it considers also the time distribution of the rainfall, the initial rainfall losses to interception and depression, storage and an infiltration rate that decreases during the course of a storm. With the SCS method, the direct runoff can be calculated for any storm, either real or fabricated, by subtracting infiltration and other losses from the rainfall to obtain the precipitation excess (runoff volume). Details of the methodology can be found in the [SCS National Engineering Handbook](#), Section 4.

Two types of hydrographs are used in the SCS procedure, unit hydrographs and dimensionless hydrographs. A unit hydrograph represents the time distribution of flow resulting from one inch of direct runoff occurring over the watershed in a specified time. A dimensionless hydrograph represents the composite of many unit hydrographs. The dimensionless unit hydrograph is plotted in nondimensional units of time divided by time to peak and discharge divided by peak discharge.

Characteristics of the dimensionless hydrograph vary with the size, shape and slope of the tributary drainage area. The most significant characteristics affecting the dimensionless hydrograph shape are the basin lag and the peak discharge for a given rainfall. Basin lag is the time from the center of mass of rainfall excess to the hydrograph peak. Steep slopes, compact shape and an efficient drainage network tend to make lag time short and peaks high; flat slopes, elongated shape and an inefficient drainage network tend to make lag time long and peaks low.

2.5.2 Concepts and Equations

The following discussion outlines the basic concepts and equations utilized in the SCS method.

2.5.2.1 Rainfall-Runoff

Rainfall-Runoff Equation - A relationship between accumulated rainfall and accumulated runoff was derived by SCS from experimental plots for numerous soils and vegetative cover conditions. Data for land-treatment measures, such as contouring and terracing, from experimental watersheds were included. The equation was developed mainly for small watersheds from which only daily rainfall and watershed data are ordinarily available. It was developed from recorded storm data that included the total amount of rainfall in a calendar day but not its distribution with respect to time. The SCS runoff equation is therefore a method of estimating direct runoff from 24-hr or 1-day storm rainfall. The equation is:

$$Q = (P - I_a)^2 / (P - I_a) + S \quad (2.2)$$

Where:

Q = accumulated direct runoff, in.

P = accumulated rainfall (potential maximum runoff), in.

I_a = initial abstraction including surface storage, interception and infiltration prior to runoff, in.

S = potential maximum retention, in.

The relationship between I_a and S was developed from experimental watershed data. It eliminates the need for estimating I_a for common usage. The empirical relationship used in the SCS runoff equation is:

$$I_a = 0.2S \quad (2.3)$$

By substituting 0.2S for I_a in equation 2.3, the SCS rainfall-runoff equation becomes:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \quad (2.4)$$

S is related to the soil and cover conditions of the watershed through the curve number (CN) or runoff factor (See Section 2.6.3.1). CN has a range of 0 to 100, and S is related to CN by:

$$S = (1000 / CN) - 10 \quad (2.5)$$

Drainage Area - The drainage area of a watershed is determined from topographic maps and field surveys. For large drainage areas it might be necessary to divide the area into sub-drainage areas to account for major land use changes, to obtain analysis results at different points within the drainage area, or to locate stormwater drainage facilities and assess their effects on the flood flows. Also a field inspection of existing or proposed drainage systems should be made to determine if the natural drainage divides have been altered. These alterations could make significant changes in the size and slope of the subdrainage areas.

Rainfall - The SCS method is based on a 24-hr storm event with various time distributions, depending on the watershed location. The Type II storm distribution was a "typical" time distribution which the SCS has prepared from rainfall records and was previously used in Lincoln, Nebraska. The MSE3 (Midwest/southeast) storm distribution is the time distribution from NOAA Atlas 14 data and shall be used as the 'typical' time distribution used for Lincoln, NE. **[Figure for MSE3 storm distribution to be provided later]** To use this distribution it is necessary for the user to obtain the 24-hr duration rainfall value for the frequency of the design storm desired from Table 2-6.

Table 2-6 City Of Lincoln 24-Hour Design Rainfall

<u>Frequency</u>	<u>24-hour Rainfall</u>	<u>Frequency</u>	<u>24-hour Rainfall</u>
2-year	3.00 in.	25-year	5.54 in.
5-year	3.74 in.	50-year	6.30 in.
10-year	4.42 in.	100-year	7.23 in.

Source: NOAA Atlas 14 data

2.5.2.2 Time of Concentration

The average slope within the watershed together with the overall length and retardance of overland flow are the major factors affecting the runoff rate through the watershed. In the SCS method, time of concentration (t_c) is defined to be the time required for water to travel from the most hydraulically distant point in a watershed to its outlet. Lag (L) can be considered as a weighted time of concentration and is related to the physical properties of a watershed, such as area, length and slope. The SCS derived the following empirical relationship between lag and time of concentration:

$$L = 0.6 t_c \quad (2.6)$$

See Appendix 2-C for information on the derivation of t_c .

In small urban areas (less than 2000 acres), a curve number method can be used to estimate the time of concentration from watershed lag. In this method the lag for the runoff from an increment of excess rainfall can be considered as the time between the center of mass of the excess rainfall increment and the peak of its incremental outflow hydrograph. The equation developed by SCS to estimate lag is:

$$L = (l^{0.8} (S + 1)^{0.7}) / (1900 Y^{0.5}) \quad (2.7)$$

Where:

- L = lag, hrs.
- L = length of mainstream to farthest divide, ft.
- Y = average slope of watershed, %
- S = $(1000/CN) - 10$
- CN = SCS curve number

The lag time may need to be corrected for the effects of urbanization. The amount of modifications to the hydraulic flow length usually must be determined from topographic maps or aerial photographs following a field inspection of the area. The modification to the hydraulic flow length not only includes pipes and channels but also the length of flow in streets and driveways.

After the lag time is adjusted for the effects of urbanization, the above equation that relates lag time and time of concentration can be used to calculate the time of concentration for use in the SCS method. Appendix 2-c presents an alternate procedure for travel time and time of concentration estimation.

2.5.3 Application

The following discussion describes the procedures used in the SCS unit hydrograph method along with recommended design aids.

2.5.3.1 Runoff Factor

In hydrograph applications, runoff is often referred to as rainfall excess or effective rainfall — all defined as the amount by which rainfall exceeds the capability of the land to infiltrate or otherwise retain the rainfall. The principal physical watershed characteristics affecting the relationship between rainfall and runoff are land use, land treatment, soil types and land slope.

Land use is the watershed cover, and it includes both agricultural and nonagricultural uses. Items such as type of vegetation, water surfaces, roads, roofs, etc. are all part of the land use. Land treatment applies mainly to agricultural land use, and it includes mechanical practices such as contouring or terracing and management practices such as rotation of crops.

The SCS uses a combination of soil conditions and land-use (ground cover) to assign a runoff factor to an area. These runoff factors, called runoff curve numbers (CN), indicate the runoff potential of an area when the soil is not frozen. The higher the CN, the higher is the runoff potential.

Soil properties influence the relationship between rainfall and runoff by affecting the rate of infiltration. The SCS has divided soils into four hydrologic soil groups based on infiltration rates (Groups A, B, C and D). These groups were previously described for the rational method. Refer to Lancaster County Soil Survey.

Consideration should be given to the effects of urbanization on the natural hydrologic soil group. If heavy equipment can be expected to compact the soil during construction or if grading will mix the surface and subsurface

soils, appropriate changes should be made in the soil group selected. Also, runoff curve numbers vary with the antecedent soil moisture conditions, defined as the amount of rainfall occurring in a selected period preceding a given storm. In general, the greater the antecedent rainfall, the more direct runoff there is from a given storm. A 5-day period is used as the minimum for estimating antecedent moisture conditions.

The following pages give a series of tables related to runoff factors. The first tables (Tables 2-8 - 2-10) give curve numbers for various land uses. These tables are based on an average antecedent moisture condition, i.e., soils that are neither very wet nor very dry when the design storm begins. Curve numbers should be selected only after a field inspection of the watershed and a review of zoning and soil maps. Table 2-11 gives conversion factors to convert average curve numbers to wet and dry curve numbers. Table 2-12 gives the antecedent conditions for the three classifications.

Table 2-7 Runoff Curve Numbers - Urban Areas¹

Cover type	Treatment ²	Hydrologic condition ³	<u>A B C D</u>			
			A	B	C	D
Fallow	Bare soil	-	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
Row Crops	Straight row (SR)	Poor	74	83	88	90
		Good	72	81	88	91
	SR + CR	Poor	67	78	85	89
		Good	71	80	87	90
	Contoured (C)	Poor	64	75	82	85
		Good	70	79	84	88
	C + CR	Poor	65	75	82	86
		Good	69	78	83	87
	Contoured & terraced (C&T)	Poor	64	74	81	85
		Good	66	74	80	82
	C&T + CR	Poor	62	71	78	81
		Good	65	73	79	81
	Small grain SR	Poor	61	70	77	80
		Good	65	76	84	88
	SR + CR	Poor	63	75	83	87
		Good	64	75	83	86
	C	Poor	60	72	80	84
		Good	63	74	82	85
	C + CR	Poor	61	73	81	84
		Good	62	73	81	84
	C&T	Poor	60	72	80	83
		Good	61	72	79	82
	C&T + CR	Poor	59	70	78	81
		Good	60	71	78	81
	Close-seeded SR or broadcast	Poor	58	69	77	80
		Good	66	77	85	89
	Legumes or C Rotation	Poor	58	72	81	85
		Good	64	75	83	85
	Meadow C&T	Poor	55	69	78	83
		Good	63	73	80	83
		Good	51	67	76	80

¹ Average runoff condition, and $I_a = 0.2S$.

² Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

³Hydrologic condition is based on a combination of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or closed-seeded legumes in rotations, (d) percent of residue cover on the land surface (good > 20%) and (e) degree of roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Source: TR-55

Table 2-9 Other Agricultural Lands¹

<u>Cover description</u>		<u>Curve numbers for hydrologic soil group</u>			
<u>Cover type</u>	<u>Hydrologic condition</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Pasture, grassland, or range-continuous forage for grazing ²	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, — protected from grazing and generally mowed for hay		30	58	71	78
Brush—brush-weed-grass mixture with brush the major element ³	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	⁴ 30	48	65	73
Woods—grass combination (orchard or tree farm) ⁵	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods ⁶	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	⁴ 30	55	70	77
Farmsteads—buildings, lanes, driveways and surrounding lots	—	59	74	82	86

¹ Average runoff condition, and $I_a = 0.2S$

² Poor: < 50% ground cover or heavily grazed with no mulch
Fair: 50 to 75% ground cover and not heavily grazed
Good: > 75% ground cover and lightly or only occasionally grazed

³ Poor: < 50% ground cover
Fair: 50 to 75% ground cover
Good: > 75% ground cover

⁴ Actual curve number is less than 30; use $CN = 30$ for runoff computations.

⁵ CNs shown were computed for areas with 50% grass (pasture) cover. Other combinations of conditions may be computed from CNs for woods and pasture.

⁶ Poor: Forest litter, small trees and brush are destroyed by heavy grazing or regular burning.
Fair: Woods grazed but not burned, and some forest litter covers the soil.
Good: Woods protected from grazing, litter and brush adequately cover soil.

Source: TR-55

Table 2-10 Conversion from Average Antecedent Moisture Conditions

To Dry and Wet Conditions

<u>CN for Average Conditions</u>	<u>Corresponding CNs For</u>	
	<u>Dry</u>	<u>Wet</u>
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50
25	12	43
15	6	30
5	2	13

Source: USDA Soil Conservation Service TP-149 (SCS-TP-149), "A Method for Estimating Volume and Rate of Runoff in Small Watersheds," revised April 1973.

**Table 2-11 Rainfall Groups for Antecedent Soil Moisture Conditions
During Growing and Dormant Seasons**

<u>Antecedent Condition</u>	<u>Conditions Description</u>	<u>Growing Season 5-day Antecedent Rainfall</u>	<u>Dormant Season 5-day Antecedent Rainfall</u>
Dry	An optimum condition of watershed soils, where soils are dry but not to the wilting point and when satisfactory plowing or cultivation takes place	Less than 1.4 in.	Less than 0.5 in.
Average	The average case for annual floods	1.4 - 2.1 in.	0.5 - 1.1 in.
Wet	When a heavy rainfall, or light rainfall and low temperatures, have occurred during the five days previous to a given storm	Over 2.1 in.	Over 1.1 in.

Source: Soil Conservation Service

2.5.3.2 Composite Curve Numbers

When a drainage area has more than one land use, a composite curve number can be calculated and used in the analysis. It should be noted that when composite curve numbers are used, the analysis does not consider the location of the specific land uses but sees the drainage area as a uniform land use represented by the composite curve number.

Composite curve numbers for a drainage area can be calculated by entering the required data into a table such as the table below:

Table 2-11 Composite Curve Number Calculations

<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>
Land Use	Curve Number	Area	% of Total Area	Composite Curve Number (Column B x Column D)

The composite curve number for the total drainage is than the sum of the composite curve numbers from column E.

The different land uses within the basin should represent a uniform hydrologic group represented by a single curve number. Any number of land uses can be included, but if their spatial distribution is important to the hydrologic analysis, then sub-basins should be developed and separate hydrographs developed and routed to the study point.

2.5.4 Limitations

Several factors, such as the percentage of impervious area and the means of conveying runoff from impervious areas to the drainage system, should be considered in computing CN for urban areas. For example, do the impervious areas connect directly to the drainage system, or do they outlet onto lawns or other pervious areas where infiltration can occur?

The curve number values given in Table 2-8 are based on directly connected impervious area. An impervious area is considered directly connected if runoff from it flows directly into the drainage system. It is also considered directly connected if runoff from it occurs as concentrated shallow flow that runs over a pervious area and then into a drainage system. It is possible that curve number values from urban areas could be reduced by not directly connecting impervious surfaces to the drainage system. For a discussion of impervious areas and their effect on curve number values, see Appendix 2-B at the end of this chapter.

2.6 Hydrologic Computer Modeling

2.6.1 Introduction

Hydrologic computer models are in widespread use. However, a model’s real utility is in monitoring changes in the watershed or asking “what if” questions. For example, what happens to the 10-year peak discharge as a portion of the watershed becomes urbanized? Or, alternatively, can the peak discharge be reduced substantially with a strategically placed detention pond? Hydrologic models will typically allow one to:

- quantify urban runoff (peaks, volumes, and in some cases, water quality),
- obtain design information (channels, pipes, reservoirs, etc.),
- determine the effects of control options (infiltration devices, retention ponds, etc.),
- perform frequency analysis, and
- provide input to economic models.

HEC-HMS (a nonproprietary model written by the U.S. Army Corps of Engineers) has been selected as the preferred SCS methodology for use in Lincoln by the Public Works & Utility Department and the Lower Platte South NRD.

2.6.2 Concepts and Equations

Modern hydrologic models generally require the user to assemble watershed elements on the computer screen in a link-node structure. That is, nodes represent sub-basins (sub-watersheds), confluences (junctions, manholes, etc.), channels/pipes, and reservoirs. These nodes are "linked" together in an arrangement that depicts how runoff passes through the watershed.

Mathematical algorithms are associated with each node. For example, a sub-basin node will require certain information from the user in order to generate a runoff hydrograph. Rainfall is a necessary input. The user will also be required to input items like area, curve number, slope, etc. With this information, the model uses internal algorithms to compute a runoff hydrograph and sends it to the next downstream element. If this element is a channel/pipe node, other data will be required to route the hydrograph to the next element. Reservoir nodes also perform routing computations. A confluence node combines two or more hydrographs from upstream sub-basins, channels/pipes, and/or reservoirs. The hydrograph(s) continue to move downstream through all of the watershed elements.

SCS procedures are embedded in most hydrologic models. HEC-HMS allow the user to model watersheds with SCS methodology. Therefore, the concepts and equations mentioned previously in this chapter are still appropriate. These include the 24-hour storm, SCS rainfall distributions, the curve number method for allocating rainfall losses, and the SCS unit hydrograph procedure. The rainfall distribution needs to be checked to ensure it is the MSE3 distribution (2.6.1). It may need to be entered manually.

2.6.3 Application

The application of a good hydrologic model is not complicated, particularly if you have a good background in hydrology and a basic understanding of the underlying algorithms used by the model. The step-by-step modeling procedure listed below is typical of most modern hydrologic models. Of course, the sequence of steps taken and the particular data requested are dependent upon the model used and the solution methodology (algorithms) chosen.

The step-by-step modeling procedure is likely to progress as follows:

- Launch the model and name your new file.
- Choose a system of units, give the project a title, and insert project comments.
- Build a watershed schematic (link/node) using the elements provided on the "tool palette."
- Choose a solution methodology (e.g., SCS) for individual watershed elements.
- Input requested data (e.g., rainfall, curve number, etc.) for each watershed element.
- Add any remaining general data (e.g., time step) and run the model.
- Interrogate individual elements from the watershed schematic for output (e.g., hydrographs).
- Evaluate the output data based on sound engineering judgement.
- Use the conclusions to determine estimates to the model for reliable output.

2.6.4 Limitations

Hydrologic models are subject to the same limitations as their underlying algorithms. For example, if SCS modeling procedures are utilized, the precautions and limitations mentioned in section 2.4.4 still apply. The major limitations of the SCS methodology are listed below.

- Curve numbers describe average conditions, particularly with regard to antecedent moisture conditions. Since a watershed or sub-watershed is described by one CN value, it should be delineated (to the extent feasible) such that it is hydrologically homogeneous. (See section 2.7.4 on weighted curve numbers.)
- Initial abstractions are assumed to be 20% of a basin's potential losses.
- Runoff from snowfall or frozen ground cannot be accounted for using SCS procedures.
- SCS procedures account for surface runoff only, not interflow or groundwater contribution.

Since many hydrologic procedures contain empirical parameters, the processes of calibration and verification can be very useful in improving model accuracy. These processes require measured rainfall and runoff data from historical events. Calibration requires that a watershed be modeled using rainfall information from a number of historical storms. Certain empirical parameters are adjusted in the process so that the modeled output matches the measured output.

Verification follows calibration. Using completely different historical rainfall information (not the same storms used for calibration), the model is run again with the adjusted empirical parameters to determine the accuracy of the results. If the modeled runoff from these new storms closely matches the measured runoff, the model is assumed to be “verified.” The process of calibration and verification is highly desirable and increases confidence in the results of a hydrologic model.

Appendix 2-A Glossary of Key Terms

Antecedent Moisture Conditions

Antecedent moisture conditions are the soil moisture conditions of the watershed at the beginning of a storm. These conditions affect the volume of runoff generated by a particular storm event. Notably they affect the peak discharge in the lower range of flood magnitudes — say below about the 15-year event threshold. As floods become more rare, antecedent moisture has a rapidly decreasing influence on runoff.

Depression Storage

Depression storage is the water stored in natural depressions within a watershed. Generally, after the depression storage is filled, runoff will commence.

Frequency

The frequency with which a given flood can be expected to occur is the reciprocal of the probability or chance that the flood will be equaled or exceeded in a given year. If a flood has a 20 percent chance of being equaled or exceeded each year, over a long period of time, the flood will be equaled or exceeded on an average of once every five years. This is also referred to as the recurrence interval or return period.

Hydraulic Roughness

Hydraulic roughness is a measure of the physical characteristics which impede the flow of water across the earth's surface, whether natural or channelized. It affects both the time response of a watershed and drainage channel as well as the channel storage characteristics.

Hydrograph

A hydrograph is a graph of the time distribution of runoff (expressed as a flow rate) from a watershed.

Hyetographs

The hyetograph is a graph of the time distribution of rainfall (usually expressed as an intensity) over a watershed.

Infiltration

Infiltration is the complex process whereby water penetrates the ground surface and is either stored in the soil pore spaces or flows to lower layers. An infiltration curve is a graph of the time distribution at which this occurs.

Interception

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

Lag Time

Lag time is defined as the time from the centroid of the excess rainfall to the peak of the hydrograph.

Peak Discharge

The peak discharge, sometimes called peak flow, is the maximum rate of flow of water passing a given point during or after a rainfall event or snowmelt.

Rainfall Excess

The rainfall excess is the water available to runoff after interception, depression storage and infiltration are satisfied.

Recurrence Interval

The time interval in which an event will occur once on the average. (i.e. a 10-year storm is expected to occur once every 10 years, on the average)

Stage

The stage of a river or other water body is the elevation of the water surface above some elevation datum.

Time Of Concentration

The time of concentration is the time it takes a drop of water falling on the hydraulically most remote point in the watershed to travel through the watershed to the outlet or design point.

Unit Hydrograph

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

Appendix 2-C

Travel Time Estimation

2.C.1 Introduction

Travel time (T_t) is the time it takes water to travel from one location to another in a watershed. It is a component of time of concentration (T_c), which is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed. T_c is computed by summing all the travel times for consecutive components of the drainage conveyance system.

Procedures and equations for calculating travel time and time of concentration are discussed in the following sections.

2.C.2 Travel Time

Water moves through a watershed as sheet flow, shallow concentrated flow, open channel flow, or some combination of these. The type that occurs is a function of the conveyance system and is best determined by field inspection.

Travel time is the ratio of flow length to flow velocity:

$$T_t = L/(3600V) \quad (2.C.1)$$

Where: T_t = travel time, hr
 L = flow length, ft
 V = average velocity, ft/s
3600 = conversion factor from sec to hrs

2.C.3 Time Of Concentration

The time of concentration is the sum of T_t values for the various consecutive flow segments:

$$T_c = T_{t1} + T_{t2} + \dots T_{tm} \quad (2.C.2)$$

Where: T_c = time of concentration, hr
 m = number of flow segments

2.C.4 Sheet Flow

Sheet flow is flow over plane surfaces. It usually occurs in the headwater of watersheds. With sheet flow, the friction value (Manning's n) is an effective roughness coefficient that includes the effect of raindrop impact; drag over the plane surface; obstacles such as litter, crop ridges and rocks; and erosion and transportation of sediment. These n values are for very shallow flow depths of about 0.1 ft or so. Table 2-C-1 gives Manning's n values for sheet flow for various surface conditions.

Sheet flow conditions are unlikely for length in excess of 300 ft. In urban residential development, sheet flow conditions may occur in rear yards and other open areas but generally ease when flow occurs between buildings. For sheet flow use Manning's kinematic solution (Overton and Meadows 1976) to compute T_t :

$$T_t = [0.42 (nL)^{0.8} / (P_2)^{0.5s^{0.4}}] \quad (2.C.3)$$

Where: T_t = travel time, min
 n = Manning's roughness coefficient (Table 2-C-1)
 L = flow length, ft
 P_2 = 2-year, 24-hr rainfall, in. (3.0 inches in Lincoln)
 s = slope of hydraulic grade line (land slope), ft/ft

Table 2-C-1
Roughness Coefficients (Manning's n) For Sheet Flow

Surface Description	n ¹
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Grasses:	
Short grass prairie	0.15
Dense grasses ²	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods: ³	
Light underbrush	0.40
Dense underbrush	0.80

¹ The n values are a composite of information compiled by Engman (1986).

² Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass and native grass mixtures.

³ When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

This simplified form of the Manning's kinematic solution is based on the following:

1. shallow steady uniform flow,
2. constant intensity of rainfall excess (rain available for runoff),
3. rainfall duration of 24 hrs, and
4. minor effect of infiltration on travel time.

Another approach is to use the kinematic wave equation. For details on using this equation consult the publication by R. M. Regan, "A Nomograph Based on Kinematic Wave Theory for Determining Time of Concentration for Overland Flow," Report Number 44, Civil Engineering Department, University of Maryland at College Park, 1971.

2.C.5 Shallow Concentrated Flow

After a maximum of 300 ft, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from equations 2.C.4 and 2.C.5, in which average velocity is a function of watercourse slope and type of channel.

$$\text{Unpaved} \quad V = 16.1345(s)^{0.5} \quad (2.C.4)$$

$$\text{Paved} \quad V = 20.3282(s)^{0.5} \quad (2.C.5)$$

Where: V = average velocity, ft/s
s = slope of hydraulic grade line (watercourse slope), ft/ft

These two equations are based on the solution of Manning's equation with different assumptions for n (Manning's roughness coefficient) and r (hydraulic radius, feet). For unpaved areas, n is 0.05 and r is 0.4 ft; for paved areas, n is 0.025 and r is 0.2 ft.

Appendix 2-C

After determining average velocity, use equation 2.C.1 to estimate travel time for the shallow concentrated flow segment.

2.C.6 Open Channels

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for bank-full elevation. Manning's equation is:

$$V = (1.49 r^{2/3} s^{1/2})/n \quad (2.C.6)$$

where:

V = average velocity, ft/s
r = hydraulic radius, ft (equal to a/p_w)
a = cross sectional flow area, ft²
p_w = wetted perimeter, ft
s = slope of the hydraulic grade line, ft/ft
n = Manning's roughness coefficient

After average velocity is computed using equation 2.C.6, T_i for the channel segment can be estimated using equation 2.C.1.

2.C.7 Reservoir Or Lake

Sometimes it is necessary to compute a T_c for a watershed which has a relatively large body of water in the flow path. This travel time is normally very small and can be assumed as zero.

One must not overlook the fact that this does not account for the travel time involved with the passage of the inflow hydrograph through spillway storage and the reservoir or lake outlet. This time is generally much longer and is added to the travel time across the lake. The travel time through lake storage and its outlet can be determined by the storage routing procedures in Chapter 6.

2.C.8 Limitations

- Manning's kinematic solution should not be used for sheet flow longer than 300 ft. Equation 2.C.3 was developed for use with the four standard SCS rainfall intensity-duration relationships. (i.e., Type II)
- In watersheds with storm drains, carefully identify the appropriate hydraulic flow path to estimate T_c. Storm drains generally handle only a small portion of a large event. The rest of the peak flow travels by streets, lawns, and so on, to the outlet. Consult Chapter 3 to determine average velocity in pipes for either pressure or nonpressure flow.
- A culvert or bridge can act as a reservoir outlet if there is significant storage behind it. Detailed storage routing procedures should be used to determine the outflow through the culvert.

Appendix 2-C

