SECTION 2 – DETERMINATION OF STORM RUNOFF

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2.1.0 GENERAL

If continuous records of the amounts of runoff from urban areas were as readily available as records of precipitation, they would provide the best source of data on which to base the design of storm drainage and flood protection systems. Unfortunately, such records are available in very few areas in sufficient quantity to permit an accurate prediction of the stormwater runoff. The accepted practice, therefore, is to relate runoff to rainfall, thereby providing a means for predicting the amount of runoff to be expected from urban watersheds at given recurrence intervals.

Numerous methods of rainfall runoff computations are available on which the design of storm drainage systems may be based. The method chosen is dependent upon the Engineer's technical familiarity and the size of the area to be analyzed. Within the method chosen the Engineer will be responsible for making assumptions as to the development characteristics of the study area.

2.2.0 EFFECTS OF URBANIZATION

It has long been recognized that urban development has a pronounced effect on the rate of runoff from a given rainfall. The hydraulic efficiency of a drainage area is generally improved by urbanization which in effect reduces the storage capacity of a watershed. This reduction of a watershed's storage capacity is a direct result of the elimination of porous surfaces, small ponds, and holding areas. This comes about by the grading and paving of building sites, streets, drives, parking lots, and sidewalks and by construction of buildings and other facilities characteristic of urban development. The result of the improved hydraulic efficiency is illustrated graphically in Figure 2-1 in Appendix B of this Manual, which is a plot of the runoff rate versus time for the same storm with two different stages of watershed development.

2.2.1 Design Assumptions For Stormflow Analysis

A. When analyzing an area for channel design purposes, urbanization of the full watershed without detention ponds shall be assumed (except as noted in paragraph E. below). Zoning maps, future land use maps, and master plans should be used as aids in establishing the anticipated surface character of the ultimate development. The selection of design runoff coefficients and/or percent impervious cover factors are explained in the following discussions of runoff calculation.

B. An exception to paragraph A. above may be granted if the channel is immediately downstream of a regional detention pond and written approval is obtained from the City Engineer.

C. In designing a storm sewer system within a residential subdivision, full development of adjoining and interior tracts without detention must be assumed.

D. In designing a storm sewer system within a commercial or multifamily subdivision, 25-year stormflows can, at the Engineer's discretion, reflect the flow reduction anticipated by future detention ponds. This applies exclusively to the flows generated by those properties contained within the subdivision. Provisions for conveyance of the 100-year undetained flows within the right-of-way or drainage easements still apply (See Section 1.2.2B.).

E. In the event the Engineer desires to incorporate the flow reduction benefits of existing upstream detention ponds, the following field investigations and hydrologic analysis will be required: (Please note that under no circumstances will the previously approved construction plans of the upstream ponds suffice as an adequate analysis. While the responsibility of the individual site or subdivision plans rests with the Engineer of record, any subsequent engineering analysis must assure that all the incorporated ponds work collectively.)

1. A field survey of the existing physical characteristics of both the outlet structure and ponding volume. Any departure from the original Engineer's design must be accounted for. If a dual use for the detention pond exists, (e.g., storage of equipment) then this too should be accounted for.

2. A comprehensive hydrologic analysis which simulates the attenuation of the contributing area ponds. This should not be limited to a linear additive analysis but rather a network of hydrographs which considers incremental timing of discharge and potential coincidence of outlet peaks.

2.3.0 METHOD OF ANALYSIS

Numerous methods of rainfall-runoff computation are available on which the design of storm drainage and flood control systems may be based. The Rational Method and the Variable Rainfall Intensity Method are accepted as adequate for drainage areas totaling 100 acres or less. For larger drainage systems, the Austin Standard Method or the Soil Conservation Service hydrologic methods (available in TR-20, HEC-1 or the Tabular/Graphical methods) should be used. The method of analysis must remain consistent when drainage areas are combined and the method which applies to the largest combined drainage area should be used. Table 2-1 is to be used as a guide in determining some of the applicable methods for calculating storm runoff. The Engineer can use other methods but must have their acceptability approved by the City Engineer.

Table 2-1
Storm Runoff Calculation Methods

Contributing Area	Runoff Methods
Less than 100 Acres	Rational or VRIM[1] SCS Tabular/Graphical[2]
100 Acres-400 Acres	SCS Tabular/Graphical[5] TR-20, HEC-1 or HEC-HMS
Greater than 400 Acres	SCS TR-20, HEC-1 or HEC-HMS

1. VRIM, Variable Rainfall Intensity Method in Section 2.4.5
2. SCS, Tabular/Graphical and TR-20 Methods in Section 2.6.4
3. It is recommended that the hand calculated SCS Tabular Method not be used for areas greater than four hundred (400) acres due to the rigorous nature of the calculations and likelihood of error

Source: City of Austin, Watershed Engineering Division

2.4.0 RATIONAL METHOD

The Rational Method is based on the direct relationship between rainfall and runoff, and is expressed by the following equation:

$$Q_p = CiA \qquad \text{(Eq. 2-1)}$$

Where:

Q_p is defined as the peak runoff in cubic feet per second. Actually, Q_p is in units of inches per hour per acre. Since this rate of in/hr/ac differs from cubic feet per second by less than one (1) percent (1 in/hr/ac = 1.008 cfs), the more common units of cfs are used.

C is the coefficient of runoff representing the ratio of peak runoff rate "Q_p" to average rainfall intensity rate "i" for a specified area "A".

i is the average intensity of rainfall in inches per hour for a period of time equal to the time of concentration (t_c) for the drainage area to the point under consideration.

A is the area in acres contributing runoff to the point of design.

The following basic assumptions are associated with the Rational Method:

A. The storm duration is equal to the time of concentration.

B. The computed peak rate of runoff to the design point is a function of the average rainfall rate during the time of concentration to that point.

C. The return period or frequency of the computed peak flow is the same as that for the design storm.

D. The necessary basin characteristics can be identified and the runoff coefficient does not vary during a storm.

E. Rainfall intensity is constant during the storm duration and spatially uniform for the area under analysis.

2.4.1 Runoff Coefficient (C)

The proportion of the total rainfall that will reach the drainage system depends on the imperviousness of the surface and the slope and ponding characteristics of the area. Impervious surfaces, such as asphalt pavements and roofs of buildings, will be subject to approximately one hundred (100) percent runoff (regardless of the slope). On-site inspections and aerial photographs may prove valuable in estimating the nature of the surfaces within the drainage area.

The runoff coefficient "C" in the Rational Formula is also dependent on the character of the soil. The type and condition of the soil determines its ability to absorb precipitation. The rate at which a soil absorbs precipitation generally decreases as the rainfall continues for an extended period of time. The soil infiltration rate is influenced by the presence of soil moisture (antecedent precipitation), the rainfall intensity, the proximity of the ground water table, the degree of soil compaction, the porosity of the subsoil, and ground slopes.

It should be noted that the runoff coefficient "C" is the variable of the Rational Method which is least susceptible to precise determination. A reasonable coefficient must be chosen to represent the integrated effects of infiltration, detention storage, evaporation, retention, flow routing and interception, all of which affect the time distribution and peak rate of runoff.

Table 2-2 presents recommended ranges for "C" values based on specific land use types.

2.4.2 Time of Concentration

The time of concentration is the time associated with the travel of runoff from an outer point which best represents the shape of the contributing areas. Runoff from a drainage area usually reaches a peak at the time when the entire area is contributing, in which case the time of concentration is the time for a drop of water to flow from the most remote point in the watershed to the point of interest. Runoff may reach a peak prior to the time the entire drainage area is contributing. Sound engineering judgment should be used to determine the time of concentration. The time of concentration to any point in a storm drainage system is a combination of the sheet flow (overland), the shallow concentrated flow and the channel flow, which includes storm sewers. The minimum time of concentration for any area shall be five (5) minutes.

A. **Sheet Flow.** Sheet flow is shallow flow over land surfaces which usually occurs in the headwaters of streams. The Engineer should realize that sheet flow occurs for only very short distances in urbanized conditions. Urbanized areas are assumed to have sheet flow of three hundred (300) feet or less. The following equation 2-2 has been developed for sheet flow of less than three hundred (300) feet.

$$t_c = Ln/(42s^{0.5}) \qquad \text{(Eq. 2-2)}$$

where,

t_c = Time of concentration in minutes
L = Length of the reach in ft.
n = Manning's n (see Table 2-3)
s = Slope of the ground in ft/ft

B. **Shallow Concentrated Flow.** After a maximum of three hundred (300) feet sheet flow becomes shallow concentrated flow. The time of concentration for shallow concentrated flows can be computed from equation 2-3 which is as follows:

$$t_c = Ln/(60s^{0.5}) \qquad \text{(Eq. 2-3)}$$

where,

t_c = Time of concentration in minutes
L = Length of the reach in ft.
n = Manning's n (see Table 2-3)
s = Slope of the ground in ft/ft

C. **Channel or Storm Sewer Flow.** The velocity in an open channel or a storm sewer not flowing full can be determined by using Manning's Equation. Channel velocities can also be determined by using backwater profiles. Usually, average flow velocity is determined assuming a bank-full condition. The details of using Manning's equation and selecting Manning's "n" values for channels can be obtained from Section 6 of this Manual.

For full flow storm sewer conditions (pressure flow) the following equation should be applied:

$$V = Q/A \qquad \text{(Eq. 2-4)}$$

Where:

V = Average velocity, ft/s
Q = Design discharge, cfs
A = Cross-sectional area, ft^2

TABLE 2-2
RATIONAL METHOD RUNOFF COEFFICIENTS FOR COMPOSITE ANALYSIS
Runoff Coefficient (C)

Character of Surface	Return Period						
	2 Years	5 Years	10 Years	25 Years	50 Years	100 Years	500 Years
DEVELOPED							
Asphaltic	0.73	0.77	0.81	0.86	0.90	0.95	1.00
Concrete	0.75	0.80	0.83	0.88	0.92	0.97	1.00
Grass Areas (Lawns, Parks, etc.)							
<u>Poor Condition</u>* Flat, 0-2% Average, 2-7% Steep, over 7%	 0.32 0.37 0.40	 0.34 0.40 0.43	 0.37 0.43 0.45	 0.40 0.46 0.49	 0.44 0.49 0.52	 0.47 0.53 0.55	 0.58 0.61 0.62
<u>Fair Condition</u>** Flat, 0-2% Average, 2-7% Steep, over 7%	 0.25 0.33 0.37	 0.28 0.36 0.40	 0.30 0.38 0.42	 0.34 0.42 0.46	 0.37 0.45 0.49	 0.41 0.49 0.53	 0.53 0.58 0.60
<u>Good Condition</u>*** Flat, 0-2% Average, 2-7% Steep, over 7%	 0.21 0.29 0.34	 0.23 0.32 0.37	 0.25 0.35 0.40	 0.29 0.39 0.44	 0.32 0.42 0.47	 0.36 0.46 0.51	 0.49 0.56 0.58
UNDEVELOPED							
<u>Cultivated</u> Flat, 0-2% Average, 2-7% Steep, over 7%	 0.31 0.35 0.39	 0.34 0.38 0.42	 0.36 0.41 0.44	 0.40 0.44 0.48	 0.43 0.48 0.51	 0.47 0.51 0.54	 0.57 0.60 0.61

TABLE 2-2 (Continued)

RATIONAL METHOD RUNOFF COEFFICIENTS FOR COMPOSITE ANALYSIS
Runoff Coefficient (C)

Character of Surface	Return Period						
	2 Years	5 Years	10 Years	25 Years	50 Years	100 Year	500 Years
Pasture/Range							
Flat, 0-2%	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2-7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.37	0.40	0.42	0.46	0.49	0.53	0.60
Forest/Woodlands							
Flat, 0-7%	0.22	0.25	0.28	0.31	0.35	0.39	0.48
Average, 2-7%	0.31	0.34	0.36	0.40	0.43	0.47	0.56
Steep, over 7%	0.35	0.39	0.41	0.45	0.48	0.52	0.58

* Grass cover less than 50 percent of the area.
** Grass cover on 50 to 75 percent of the area.
*** Grass cover larger than 75 percent of the area.

Source: 1. Rossmiller, R.L. “The Rational Formula Revisited.”
2. City of Austin, Watershed Engineering Division

TABLE 2-3 MANNING'S "n" FOR OVERLAND FLOW AND SHALLOW CONCENTRATED FLOW	
Manning's "n"	Condition
0.016	Concrete (rough or smoothed finish)
0.02	Asphalt
0.1	0-50% vegetated ground cover, remaining bare soil or rock outcrops, minimum brush or tree cover
0.2	50-90% vegetated ground cover, remaining bare soil or rock outcrops, minimum- medium brush or tree cover
0.3	100% vegetated ground cover, medium- dense grasses (lawns, grassy fields etc.) medium brush or tree cover
0.6	100% vegetated ground cover with areas of heavy vegetation (parks, green- belts, riparian areas etc.) dense under- growth
Source: City of Austin, Watershed Engineering Division	

2.4.3 Rainfall Intensity (i)

Rainfall intensity (i) is the average rainfall rate in inches per hour, and is selected on the basis of design rainfall duration and design frequency of occurrence. The design duration is equal to the time of concentration for the drainage area under consideration. The design frequency of occurrence is a statistical variable which is established by design standards or chosen by the Engineer as a design parameter.

The selection of the frequency criteria is necessary before applying any hydrologic method. Storm drainage improvements in Round Rock must be designed to intercept and carry the runoff from a twenty-five (25) year frequency storm, with an auxiliary or overflow system capable of carrying a one hundred (100) year frequency storm.

The rainfall intensity used in the rational method is read from the intensity-duration-frequency curves based on the selected design frequency and design duration. The Austin intensity-duration-frequency curves, developed in 1975, used rainfall data recorded at the Austin Station of the U.S. National Weather Service. This data includes a forty-five (45) year record of rainfall for most durations from five (5) minutes to twenty-four (24) hours and a seventy-four (74) year record of rainfall for the twenty four (24) hour duration.

The precipitation values for different frequency storms and durations are given in Table 2-5. The Austin intensity-duration-frequency curves are shown in Figure 2-2 in Appendix B of this Manual.

Table 2-4
Precipitation Values in Austin (Inches)

Duration (Minutes)	Return Period						
	2 Years	5 Years	10 Years	25 Years	50 Years	100 Years	500 Years
5	.54	.64	.72	.82	.91	.99	1.23
10	.90	1.08	1.21	1.40	1.56	1.70	2.14
15	1.15	1.40	1.58	1.84	2.05	2.25	2.86
30	1.62	2.03	2.31	2.73	3.06	3.38	4.38
60	2.07	2.69	3.10	3.72	4.19	4.66	6.16
120	2.45	3.32	3.90	4.74	5.39	6.03	8.11
180	2.64	3.68	4.37	5.36	6.11	6.87	9.32
Source: City of Austin, Watershed Engineering Division							

The following equation represents mathematically the Austin intensity-duration-frequency curves:

$$i = a/(t+b)^c \qquad \text{(Eq. 2-5)}$$

Where,

i = Average rainfall intensity, inches per hour
t = Storm duration, minutes
a, b and c = Coefficients for different storm frequencies

The values for a, b, and c are listed in Table 2-5:

Table 2-5 Austin Intensity-Duration-Frequency Curve Coefficients			
Storm Frequency	**a**	**b**	**c**
2-year	106.29	16.81	0.9076
5-year	99.75	16.74	0.8327
10-year	96.84	15.88	0.7952
25-year	111.07	17.23	0.7815
50-year	119.51	17.32	0.7705
100-year	129.03	17.83	0.7625
500-year	160.57	19.64	0.7449
Source: City of Austin, Watershed Engineering Division			

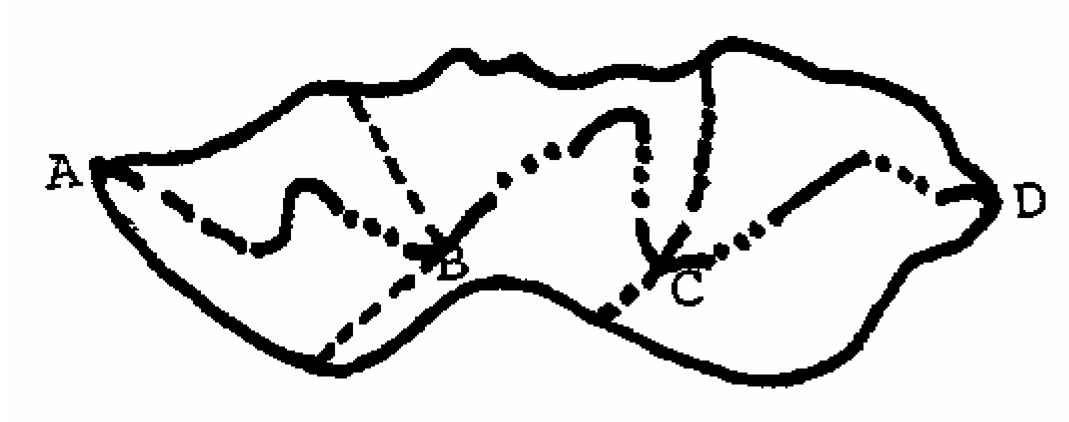
The intensity-duration-frequency curves and the intensity-duration equations are applicable for all design frequencies shown and for storm durations from five (5) minutes to 3 hours. They are required for use in determining peak flows by the Rational Method or other appropriate methods.

2.4.4 Drainage Area (A)

The size (acres) of the watershed needs to be determined for application of the Rational Method. The area may be determined through the use of maps, supplemented by field surveys where topographic data has changed or where the contour interval is too great to distinguish the direction of flow. The drainage divide lines are determined by street layout, lot grading, structure configuration and orientation, and many other features that are created by the urbanization process.

<u>Example 2-1</u>

An urbanized watershed is shown on the following figure. Three types of flow conditions exist between the most distant point in the watershed and the outlet. The calculation of time of concentration and travel time in each reach is as follows:



Reach	Description of Flow	Slope (%)	Length (Ft.)	Drainage Area (Acre)	"n" Value
A to B	Sheet flow (grass lawn)	4.5	300	3	0.3
B to C	Shallow concentrated flow (gutter)	2.0	840	20	0.016
C to D	Storm drain with inlets n=0.015 D=3	1.5	1,200	30	

For reaches A-B and B-C, the time of concentration can be calculated from Equations 2-2 and 2-3.

$t_{c\ (A\text{-}B)} = 300(0.3)/42(s)^{0.5}$

$= 2.14/(0.045)^{0.5}$

$= 10.1$ min.

$t_{c\ (B\text{-}C)} = 840(0.016)/60(s)^{0.5}$

$= 0.22/(0.02)^{0.5}$

$= 1.6$ min.

The flow velocity in reach C-D needs to be calculated from Manning's Equation, using the assumption of full pipe flow, as follows:

$V_{C\text{-}D} = (1.49/n)\ R^{0.67} s^{0.5}$

$= (1.49/n)\ (D/4)^{0.67} s^{0.5}$

$= (1.49/0.015)\ (3/4)^{0.67}(0.015)^{0.5}$

$= 10.0$ ft/s

The runoff coefficients (C) for the three (3) areas are given as follows for the 100 year storm. The time of concentration (t_c) is calculated by dividing the length by the velocity.

Reach	Length (ft.)	Velocity (fps)	t_c (min)	C	Area (acre)
A-B	300	--	10.1	0.41	3
B-C	840	--	1.6	0.85	20
C-D	1200	10.0	2.0	0.81	30
			13.7		53

The intensity (i) of the 100 year storm (from Figure 2-2 in Appendix B of this Manual) for 13.7 minutes = 9.2 inches per hour.

The composite runoff coefficient (C) = (0.41 X 3 + 0.85 X 20 + 0.81 X 30)/53= 0.80

Thus the peak flow Qp = CiA = 0.80 X 9.2 in/hr X 53 acre = 390 cfs

2.4.5 Variable Rainfall Intensity Method

The Variable Rainfall Intensity Method is one of the methodologies which uses the peak flow (Qp) calculated from the Rational Method to develop the hypothetical storm hydrographs. The detailed information on this method can be found in the Bibliograhpy, Item 2-5 of this Manual. The following example illustrates the application of the variable rainfall intensity method technique in constructing a ten (10) year design storm hydrograph.

Example 2-2

Variable Rainfall Intensity Method

Given: A drainage area, when fully developed, will have the following characteristics:

Drainage area = one hundred (100) acres
Runoff coefficient C = 0.45
Design rainfall frequency: ten (10) year
Austin rainfall intensity-duration-frequency curves (Figure 2-2 in Appendix B of this Manual)
Time of concentration = forty (40) minutes.

Find: The ten (10) year design storm and resulting flood hydrograph.

Solution: The solution is outlined in Table 2-6 which shows the development of the design ten (10) year frequency storm and Table 2-7 which shows the computation of the design ten (10) year flood hydrograph.

The computation procedures for Table 2-6 are explained as follows:

Column 1: Duration (minutes) = length of storm.

Column 2: Rainfall Intensity read from Figure 2-2 in Appendix B of this manual corresponding to the duration time in Column 1.

Column 3: Accumulated Depth (inches) = total precipitation for storm of specified duration (from Table 2-11).

Column 4: Incremental Depth (inches) = difference in total precipitation between specified duration and duration of five (5) minutes less than specified duration (e.g., P35 minutes - P30 minutes).

Column 5: Incremental Intensity (inches/hour) = Incremental Depth (inches) x (60 minutes/hour)/(five (5) minutes).

Table 2-6
Development Of A Ten (10) Year Frequency Storm

Duration (Min) (1)	Intensity (In/hr) (2)	Accumulated Depth (In) (3)	Incremental Depth (In) (4)	Incremental Intensity (In/hr) (5)
5	8.64	.034	0.34	.41
10			0.36	.43
15	6.16	.108	.038	.46
20			.04	.48
25	5.00	.19	.04	.48
30			.05	.60
35	4.30	.29	.05	.60
40			.06	.72
45	3.73	.41	.06	.72
50			.07	.84
55	3.33	.56	.08	.96
60			.09	1.08
65	3.00	.76	.11	1.32
70			.13	1.56

75	2.74	1.07	.18	2.16
Table 2-6 (Continued) Development Of A Ten (10) Year Frequency Storm				
Duration (Min) (1)	**Intensity (In/hr) (2)**	**Accumulated Depth (In) (3)**	**Incremental Depth (In) (4)**	**Incremental Intensity (In/hr) (5)**
80			.24	2.88
85	2.50	1.67	.36	4.32
90			.72	8.64
95	2.32	2.89	.5	6.0
100			.29	3.48
105	2.17	3.38	.20	2.4
110			.15	1.8
115	2.05	3.65	.12	1.44
120			.1	1.2
125	1.94	3.83	.08	.96
130			.08	.96
135	1.85	3.98	.07	.84
140			.06	.72
145	1.77	4.09	.05	.60
150			.05	.60
155	1.69	4.19	.05	.60
160			.04	.48
165	1.62	4.27	.04	.48
170			.04	.48
175	1.56	4.34	.03	.36
180			.03	.36
185	1.50	4.38		.36

Table 2-7 illustrates the computed 10 year flood hydrograph for the drainage area described in Table 2-6. Referring to Table 2-7, the columns are identified and computed as follows:

Column 1: Time (minutes) = time from the beginning of the storm.

Column 2: i (inches/hour) = incremental intensities (from Table 2-6).

Column 3: Sum (i) = summation of all incremental intensities to the specified time.

Column 4: "Sum" (i lagged) = column 3 displaced a total time equal to the time of concentration for the area producing this hydrograph.

Column 5: (3) - (4) = column 3 - column 4.

Column 6: q_{tc}= column 5 divided by the number of time increments in the time of concentration for the area producing this hydrograph. This column expresses the average intensity over a period of time equal to the time of concentration for the area producing this hydrograph, as measured at the specified chronological time.

Column 7: Q (cubic feet per second) = column 6 x “C” x A (for the area producing this hydrograph). This column is for the rising limb calculation.

Column 8: Time Folded revised times and flows for falling limb of hydrograph; falling limb is mirror image of rising limb, but expanded to twice the length. Intermediate values can be linearly interpolated from neighboring values, since five (5) minute increments doubled to ten (10) minute increments leave out intervening values.

The computations were stopped in column 7 when the rising limb of the hydrograph reached its peak value. At this point, the time scale can be folded as shown in column 8. Doubling the time increments for the falling limb serves to double the volume that would have been under that portion of the runoff hydrograph. The volume under the entire discharge hydrograph will be three (3) times that under the rising limb.

With this assumption, the volume of runoff expressed as a percentage from an area with a runoff coefficient of 0.45 becomes approximately sixty seven and one half (67.5) percent rather than forty-five (45) percent of the rainfall. In this procedure the C value from the Rational Method formula represents the ratio of the peak runoff to the average rainfall intensity rate for a period equal to the time of concentration and not a simple runoff to rainfall ratio.

Table 2-7
Runoff Computations From A 100 Acre Area With A Time Of Concentration Of 40 Minutes And C = 0.45

Time (Min) (1)	I_{10} **(In/Hr) (2)**	Sum I_{10} **(3)**	Sum I_{10} **(Lagged 40 min) (4)**	Time (3) - (4) (5)	Q_{40} **(In/Hr) (6)**	Q (cfs) (7)	Folded (8)
0							330
5	0.41	0.41		.41	.05	2.3	320
10	0.43	0.84		.84	.10	4.5	310
15	0.46	1.3		1.3	.16	7.2	300
20	0.48	1.78		1.78	.22	9.9	290
25	0.48	2.26		2.26	.28	12.6	280
30	0.6	2.86		2.86	.36	16.2	270
35	0.6	3.46		3.46	.43	19.3	260
40	0.72	4.18		4.18	.52	23.4	250
45	0.72	4.9	.41	4.5	.56	25.2	240
50	0.84	5.7	.84	4.9	.61	27.4	230
55	0.96	6.7	1.3	5.4	.67	30.1	220
60	1.08	7.8	1.78	6.0	.75	33.7	210
65	1.32	9.1	2.26	6.8	.85	38.2	200
70	1.56	10.7	2.86	7.8	.97	43.6	190

Table 2-7 (Continued) Runoff Computations From A 100 Acre Area With A Time Of Concentration Of 40 Minutes And C = 0.45							
Time (Min) (1)	**I_{10} (In/Hr) (2)**	**Sum I_{10} (3)**	**Sum I_{10} (Lagged 40 min) (4)**	**Time (3) - (4) (5)**	**Q_{40} (In/Hr) (6)**	**Q (cfs) (7)**	**Folded (8)**
75	2.16	12.8	3.46	9.3	1.16	52.2	180
80	2.88	15.7	4.18	11.5	1.44	64.8	170
85	4.32	20.0	4.9	15.1	1.89	85.1	160
90	8.64	28.7	5.7	23.0	2.87	129.1	150
95	6.0	34.7	6.7	28.0	3.5	157.5	140
100	3.48	38.1	7.8	30.3	3.8	171.0	130
105	2.4	40.5	9.1	31.4	3.92	176.4	120
110	1.8	42.3	10.7	31.6	3.95	177.7	(peak)
115	1.44	43.8	12.8	31.0	3.87	174.1	

2.5.0 SOIL CONSERVATION SERVICE METHODS

The Soil Conservation Service (SCS) hydrologic methods have been widely used by engineers and hydrologists for analyses of small urban watersheds. These methods resulted from extensive analytical work using a wide range of statistical data concerning storm patterns, rainfall-runoff characteristics and many hydrologic observations in the United States. The SCS utilizes a twenty-four (24) hour storm duration, which is considered to be acceptable for the Austin area; however, the design storm most representative of the Austin area has a three (3) hour duration. It should be noted that if the SCS storms are applied, the Type III distribution should be used.

The SCS methods can be applied to urban drainage areas of any size. A brief explanation of the runoff curve numbers, the tabular and graphical methods and the TR-20 method are introduced in this Section. The Supplemental Section 2.7.0 for the Soil Conservation Service hydrology includes the rainfall-runoff relationship and the dimensionless Unit Hydrograph. For detailed information, the user is referred to the following Soil Conservation Service publications. They are:

NEH-4: "Hydrology," Section 4, National Engineering Handbook
TR-20: Computer Program for Project Formulation, Hydrology
TR-55: Urban Hydrology for Small Watersheds
TP-149: A Method for Estimating Volume and Rate of Runoff in Small Watersheds

2.5.1 Austin Three (3) Hour Storm Rainfall Distributions

The three (3) hour design storm duration for Austin was selected after consideration of rainfall-runoff data and watershed flow-conveyance properties in the Austin area. This determination was made in 1977 with the derivation of the Austin Standard Method. Table 2-8 is a listing of the cumulative rainfall values for six (6) and three (3) hour storms with various return frequencies. Table 2-9 gives the incremental rainfall values for both five (5) and ten (10) minute increments. Tables 2-8 and 2-9 are given for use in the TR-20, and HEC-HMS programs.

2.5.2 Soil Conservation Service Runoff Curve Numbers

The Soil Conservation Service (SCS) has developed an index, the runoff curve number, to represent the combined hydrologic effect of soil type, land use, agricultural land treatment class, hydrologic condition, and antecedent soil moisture. These watershed factors have the most significant impact in estimating the volume of runoff, and can be assessed from soil surveys, site investigations and land use maps.

The curve number is an indication of the runoff producing potential of the drainage area for a given antecedent soil moisture condition, and it ranges in value from zero (0) to one hundred (100). The SCS runoff curve numbers are grouped into three (3) antecedent soil moisture conditions -- Antecedent Moisture Condition I, Antecedent Moisture Condition II and Antecedent Moisture Condition III. Values of runoff curve numbers for all three (3) conditions may be computed following guidelines in "Hydrology, Section 4," National Engineering Handbook. Antecedent Moisture Condition I is the dry soil condition and Antecedent Moisture Condition III is the wet soil condition. Antecedent Moisture Condition II is normally considered to be the average condition.

Table 2-8 Austin Three (3) Hour Design Storm Distributions Cumulative Values (inches)						
Time (Minutes)	**2-Year**	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**
5	0.013	0.025	0.034	0.044	0.052	0.061
10	0.027	0.052	0.070	0.091	0.108	0.13
15	0.042	0.081	0.108	0.14	0.17	0.19
20	0.059	0.112	0.15	0.19	0.23	0.27
25	0.077	0.15	0.19	0.25	0.30	0.34
30	0.097	0.18	0.24	0.31	0.37	0.43
35	0.12	0.22	0.29	0.38	0.44	0.52
40	0.15	0.27	0.35	0.45	0.53	0.61
45	0.17	0.32	0.41	0.53	0.62	0.72
50	0.21	0.37	0.48	0.62	0.73	0.84
55	0.25	0.44	0.56	0.72	0.84	0.98
60	0.30	0.51	0.65	0.84	0.98	1.13
65	0.36	0.60	0.76	0.98	1.14	1.31
70	0.43	0.71	0.90	1.15	1.33	1.53
75	0.54	0.86	1.07	1.36	1.57	1.80
80	0.69	1.06	1.31	1.65	1.90	2.17

Table 2-8 (Continued) Austin Three (3) Hour Design Storm Distributions Cumulative Values (inches)						
Time (Minutes)	**2-Year**	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**
85	0.94	1.39	1.67	2.19	2.40	2.72
90	1.48	2.03	2.39	3.01	3.31	3.71
95	1.84	2.47	2.89	3.53	3.96	4.43
100	2.03	2.72	3.18	3.88	4.35	4.87
105	2.16	2.89	3.38	4.13	4.63	5.18
110	2.24	3.02	3.53	4.32	4.85	5.43
115	2.31	3.12	3.65	4.47	5.03	5.63
120	2.36	3.20	3.75	4.60	5.17	5.79
125	2.41	3.27	3.84	4.71	5.30	5.94
130	2.44	3.33	3.91	4.80	5.41	6.06
135	2.47	3.38	3.98	4.89	5.51	6.17
140	2.50	3.43	4.04	4.96	5.60	6.28
145	2.52	3.47	4.09	5.03	5.68	6.37
150	2.55	3.51	4.14	5.10	5.75	6.46
155	2.56	3.54	4.19	5.16	5.82	6.54
160	2.58	3.57	4.23	5.21	5.89	6.61

Table 2-8 (Continued) Austin Three (3) Hour Design Storm Distributions Cumulative Values (inches)						
Time (Minutes)	**2-Year**	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**
165	2.60	3.60	4.27	5.26	5.95	6.68
170	2.61	3.63	4.30	5.31	6.00	6.75
175	2.63	3.66	4.34	5.36	6.06	6.81
180	2.64	3.68	4.37	5.40	6.11	6.87
Note: These values must be entered as total, not incremental, values in a rainfall-runoff model						
Source: City of Austin, Watershed Engineering Division						

Table 2-9
Austin Three (3) Hour Design Storm Distributions
Incremental Values (inches) 5 & 10 Minute Patterns

Time (Minutes)	2-year		5-year		10-year		25-year		50-year		100-year	
	5 min.	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.
0	0		0		0		0		0		0	
5	0.013		0.025		0.034		0.044		0.052		0.061	
10	0.014	0.028	0.027	0.053	0.036	0.071	0.047	0.093	0.056	0.110	0.064	0.126
15	0.015		0.029		0.038		0.050		0.058		0.068	
20	0.017	0.033	0.031	0.061	0.041	0.081	0.053	0.104	0.062	0.123	0.073	0.143
25	0.018		0.034		0.044		0.057		0.067		0.077	
30	0.020	0.039	0.037	0.072	0.047	0.093	0.061	0.121	0.072	0.141	0.083	0.163
35	0.023		0.040		0.051		0.067		0.077		0.089	
40	0.025	0.049	0.044	0.086	0.057	0.111	0.073	0.142	0.085	0.166	0.098	0.192
45	0.029		0.049		0.063		0.080		0.094		0.108	
50	0.034	0.065	0.056	0.106	0.070	0.136	0.089	0.174	0.104	0.203	0.119	0.232
55	0.04		0.064		0.079		0.101		0.117		0.135	
60	0.048	0.091	0.075	0.144	0.092	0.178	0.117	0.226	0.135	0.261	0.154	0.298
65	0.059		0.090		0.109		0.138		0.159		0.181	
70	0.076	0.143	0.112	0.212	0.134	0.255	0.168	0.319	0.192	0.367	0.219	0.417

Table 2-9 (Continued) Austin Three (3) Hour Design Storm Distributions Incremental Values (inches) 5 & 10 Minute Patterns												
Time (Minutes)	2-year		5-year		10-year		25-year		50-year		100-year	
	5 min.	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.	5 min	10 min.
75	0.104		0.146		0.172		0.214		0.244		0.275	
80	0.153	0.277	0.205	0.376	0.238	0.438	0.291	0.538	0.329	0.610	0.369	0.685
85	0.254		0.324		0.368		0.540		0.494		0.549	
90	0.540	0.896	0.640	1.077	0.720	1.214	0.820	1.340	0.910	1.558	0.990	1.703
95	0.356		0.437		0.494		0.520		0.648		0.713	
100	0.193	0.447	0.253	0.577	0.290	0.658	0.352	0.852	0.398	0.892	0.443	0.992
105	0.124		0.171		0.200		0.247		0.281		0.316	
110	0.088	0.192	0.127	0.273	0.151	0.323	0.189	0.403	0.216	0.460	0.244	0.519
115	0.067		0.100		0.121		0.151		0.175		0.198	
120	0.053	0.112	0.082	0.172	0.100	0.209	0.127	0.265	0.146	0.305	0.167	0.348
125	0.043		0.069		0.086		0.109		0.126		0.144	
130	0.036	0.076	0.060	0.124	0.075	0.154	0.096	0.197	0.111	0.228	0.124	0.259
135	0.031		0.052		0.066		0.085		0.099		0.113	
140	0.027	0.056	0.047	0.096	0.059	0.122	0.076	0.156	0.089	0.183	0.102	0.210

Table 2-9 (Continued) Austin Three (3) Hour Design Storm Distributions Incremental Values (inches) 5 & 10 Minute Patterns												
Time (Minutes)	**2-year**		**5-year**		**10-year**		**25-year**		**50-year**		**100-year**	
	5 min.	**10 min.**	**5 min**	**10 min.**	**5 min**	**10 min.**	**5 min**	**10 min.**	**5 min**	**10 min.**	**5 min**	**10 min.**
145	0.024		0.042		0.054		0.069		0.081		0.094	
150	0.021	0.044	0.038	0.078	0.050	0.101	0.064	0.131	0.075	0.152	0.087	0.176
155	0.019		0.035		0.046		0.060		0.069		0.080	
160	0.017	0.035	0.032	0.066	0.042	0.086	0.055	0.112	0.065	0.132	0.074	0.151
165	0.016		0.030		0.040		0.051		0.061		0.070	
170	0.015	0.030	0.028	0.057	0.037	0.075	0.048	0.098	0.057	0.113	0.066	0.134
175	0.014		0.026		0.035		0.046		0.054		0.062	
180	0.013	0.026	0.024	0.049	0.033	0.067	0.043	0.087	0.051	0.103	0.059	0.120

However, studies of hydrologic data indicate that Antecedent Moisture Condition II is not the average throughout Texas. Instead, investigations have shown that the average condition ranges from Antecedent Moisture Condition I in west Texas to between Antecedent Moisture Condition II and Antecedent Moisture Condition III in east Texas. The values given in Table 2-10 are for an Antecedent Moisture Condition II. If it is desired to change to an Antecedent Moisture Condition I or Ill, the adjustments given in TR-55 or "Hydrology, Section 4," National Engineering Handbook should be used.

The SCS has classified more than four thousand (4,000) soils into four (4) hydrologic groups, identified by the letters A, B, C, and D, to represent watershed characteristics.

Group A: (Low runoff potential). Soils having a high infiltration rate even when thoroughly wetted and consisting chiefly of deep, well-drained to excessively drained sands or gravels.

Group B: Soils having a moderate infiltration rate when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse texture.

Group C: Soils having a slow infiltration rate when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water or soil with moderately fine to fine texture.

Group D: (High runoff potential). Soils having a very slow infiltration rate when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

The list of most soils in the United States along with their hydrologic soil classification is given in the TR-55 publication. The minimum infiltration rates for the four (4) soil groups are:

Group	Minimum Infiltration Rate (in/hr)
A	0.30 - 0.45
B	0.15 - 0.30
C	0.05 - 0.15
D	0.00 - 0.05

Table 2-13 lists the curve numbers for the four (4) soil groups under various land uses, land treatment and hydrologic conditions. In order to determine the soil classifications in the Round Rock area, the SCS Soil Survey of Williamson or Travis County, Texas should be used.

Table 2-10 SCS Runoff Curve Numbers for Urban Areas and Agricultural Lands					
Cover Description		**Curve Numbers for Hydrologic Soil Group**			
Cover type and Hydrologic Condition	**Average % Impervious Area[1]**	**A**	**B**	**C**	**D**
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)					
Poor condition (grass cover 50%) Fair condition (grass cover 50% to 75%) Good condition (grass cover 75%)		68 49 39	79 69 61	86 79 74	89 84 80
Impervious areas: Paved parking lots, roofs, driveways, etc. (excluding right of way)		98	98	98	98
Streets and roads: Paved; curbs and storms sewers (excluding right of way) Paved open ditches (including right of way) Gravel (including right of way) Dirt (including right of way)		98 83 76 72	98 89 85 82	98 92 89 87	98 93 91 89
Urban districts: Commercial and business Industrial	85 72	89 81	92 88	94 91	95 93

Table 2-10 (Continued) SCS Runoff Curve Numbers for Urban Areas and Agricultural Lands					
Cover Description		**Curve Numbers for Hydrologic Soil Group**			
Cover type and Hydrologic Condition	**Average % Impervious Area[1]**	**A**	**B**	**C**	**D**
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)		77	86	91	94
Agricultural lands					
Grassland, or range-continuous forage for grazing[2]	Poor Fair Good	68 49 39	79 69 61	86 79 74	89 84 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 Fair Good	48 35 30	67 56 48	77 70 65	83 77 73
Woods—grass combination (orchard or tree farm).[4]	Poor Fair Good	57 43 32	73 65 58	82 76 72	86 82 79
Woods[5]	Poor Fair Good	45 36 30	66 60 55	77 73 70	83 79 77

Table 2-10 (Continued) SCS Runoff Curve Numbers for Urban Areas and Agricultural Lands					
Cover Description		**Curve Numbers for Hydrologic Soil Group**			
Cover type and Hydrologic Condition	**Average % Impervious Area[1]**	**A**	**B**	**C**	**D**
Farmsteads—buildings, lanes, driveways and surrounding lots		59	74	82	86

1 The average percent impervious area shown was used to develop the composite curve numbers. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a curve number of ninety eight (98) and pervious areas are considered equivalent to open space in good hydrologic condition.

2 Poor: less than 50 percent ground cover or heavily grazed with no mulch.
Fair: 0 to 75 percent ground cover and not heavily grazed.
Good: greater than 75 percent ground cover and lightly or only occasionally grazed.

3 Poor: less than 50 percent ground cover.
Fair: 50 to 75 percent ground cover.
Good: greater than 75 percent ground cover.

4 Curve numbers shown were computed for areas with 50 percent woods and 50 percent grass (pasture) cover. Other combinations of conditions may be computed from the curve numbers for woods and pasture.

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

Source: Soil Conservation Service. TR-55: Urban Hydrology for Small Watersheds

2.5.3 Time of Concentration

The procedures for estimating time of concentration for the SCS method are described in the SCS's Technical Release 55 (TR-55). Three (3) types of flow (sheet flow, shallow concentrated flow and channel flow) are considered.

In hydrograph analysis, the time of concentration is the time from the end of excess rainfall to the point of inflection on the falling limb of the hydrograph. The time of concentration determines the shape of the runoff hydrograph. The time of concentration determines the shape of the runoff hydrograph. Times of concentration are required for the existing and developed conditions to adequately model the impact of the development on stormwater runoff. In general, times of concentration for the developed condition should be calculated based on conservative assumptions concerning the increased hydraulic efficiency expected with an ultimate developed condition. For instance, while sheet flow for existing conditions is typically limited to three hundred (300) feet, sheet flow for developed conditions should be limited to one hundred fifty (150) feet.

2.5.4 Peak Flow Calculation

The SCS has presented several methods for computing runoff hydrographs for drainage areas. The Tabular, Graphical and TR-20 methods are considered acceptable for the Austin area. The parameters required to calculate the hydrograph are the rainfall distribution, runoff curve numbers, time of concentration and drainage area.

A. **Tabular Method.** The Tabular Method can be used to develop composite flood hydrographs at any point within a watershed by dividing the watershed into subareas. The method is useful for watersheds where runoff hydrographs are needed from nonhomogeneous areas, i.e., the watershed can be divided into homogeneous sub-areas. It is especially applicable for estimating the effects of land use change in a portion of the watershed. It should be noted that the tables in the TR-55 publication for the tabular method are based on the SCS twenty-four (24) hour rainfall distributions. The engineer should apply those tables corresponding to a Type III rainfall distribution which is acceptable for the Austin area.

The basic requirement for use of this method is the tabular discharge values for the different types of storm distributions. The tabular discharge values in csm/in (cubic feet of discharge per second per square mile of watershed per inch of runoff) are given in TR-55 for a range of times of concentration from one tenth (0.1) to two (2) hours and reach travel times of zero (0) to three (3) hours. The discharge values were developed from the TR-20 program by computing hydrographs for a one square mile drainage area at selected times of concentration and routing them through stream reaches with the range of travel times indicated.

The other input needed to develop the composite flood hydrograph includes the total runoff volume (Q_v) and the drainage area (A_m). The equation for calculating the flow at any time is:

$$q = q_t A_m Q_v \qquad \text{(Eq. 2-6)}$$

where,

q = Hydrograph ordinate at hydrograph time t, cfs
q_t = Individual value read from the tabular discharge tables, CSM/inch
A_m = Drainage area of individual subwatershed, mi^2
Q_v = Total runoff volume, inches.

The composite flood hydrograph is obtained by submission of the individual subarea hydrographs at each time step. For measuring runoff from a nonhomogeneous watershed, the subdivision of the watershed into relatively homogeneous subareas is required. For additional information regarding the Tabular method the SCS publication TR-55 should be consulted.

B. **Graphical Method.** As in the Tabular Method the Graphical Method is based on hydrograph analyses using the TR-20 computer program. The Graphical Method provides a determination of peak discharge only. If a hydrograph is needed or watershed subdivision is required, use the Tabular or TR-20 methods. The TR-55 lists in detail the limitations of the Graphical Method and the engineer should be well aware of these before proceeding. The input requirements for the Graphical Method are as follows:

1. t_c (hrs)
2. Drainage Area (mi^2)
3. Type III rainfall distribution
4. 24-hr. rainfall (in.)
5. CN

The peak discharge equation for the graphical method is:

$$q_p = q_u A_m Q \qquad \text{(Eq. 2-7)}$$

*q_p= peak discharge (cfs)
q_u= unit peak discharge (csm/in)
A_m= drainage area ($mi.^2$)
Q = runoff (in)

*Note the original SCS equation also has an Fp factor for pond and swamp conditions. This has been omitted since it is not applicable to the Austin region.

For additional information regarding the Graphical Method the SCS publication TR-55 should be consulted.

C. **TR-20 Method.** The TR-20 method is a computer program which develops runoff hydrographs for a watershed. The input information includes drainage area, time of concentration, SCS curve number, a specific rainfall distribution and the antecedent soil moisture condition.

The TR-20 program was developed by the SCS to assist in the hydrologic evaluation of flood events for use in analysis of water resource projects. Besides developing the runoff hydrograph from any synthetic or natural storm rainfall, the program provides the capability to route, add, store, divert or divide hydrographs to convey floodwater from the headwaters to the watershed outlets.

The program uses the procedures described in the SCS's National Engineering Handbookin "Hydrology, Section 4" except for the reach routing procedures. The modified Attenuation-Kinematic routing method is used for reach routing. Uniform rainfall depth and distribution over time are assumed over a subarea, groups of subareas or the whole watershed.

2.6.0 SUPPLEMENTAL SECTION: SOIL CONSERVATION SERVICE HYDROLOGY

2.6.1 Rainfall-Runoff Relationship

The SCS has developed a rainfall-runoff relationship to calculate the total runoff volume for a single storm. Based on the relationship between rainfall, runoff and retention (the rain not converted to runoff), an arithmetic equation for a storm without any initial abstraction can be expressed as:

$$F/S = Q/P \qquad \text{(Eq. S-1)}$$

where,

Q = Actual runoff volume
P = Rainfall (P is equal or greater than Q)
F = Actual retention after runoff begins
S = Potential maximum retention after runoff begins (S is equal to or greater than F)

The retention, S, is a constant for a particular storm because it is the maximum that can occur under the existing conditions if the storm continues without limit. The retention F varies because it is the difference between P and Q at any point on the mass curve, or:

$$F = P - Q \qquad \text{(Eq. S-2)}$$

The actual runoff (Q) can be solved as:

$$Q = P^2/(P+S) \qquad \text{(Eq. S-3)}$$

which is a rainfall-runoff relationship in which the initial abstraction is zero.

If an initial abstraction (I_a) greater than zero is considered, the amount available for runoff is P - $I_a$instead of P. By substituting (P - I_a) for P in equation S-1, the following equation results. The new arithmetic expression becomes:

$$F/S = Q/(P-I_a) \qquad \text{(Eq. S-4)}$$

where F≤S, and Q ≤ (P - I_a). The total retention for a storm consists of I_a and F. The total potential maximum retention (as P gets very large) consists of $1_a$and S.

The actual runoff is:

$$Q = ((P - I_a)+S) \quad \text{(Eq. S-5)}$$

The initial abstraction (I_a) is a function of land use, treatment and condition, interception, infiltration, depression storage, and antecedent soil moisture. An empirical analysis performed by the SCS found that the initial abstraction is estimated as:

$$I_a= 0.2\ S \quad \text{(Eq. S-6)}$$

Thus, the runoff volume (Q) can be obtained from the volume of precipitation (P) and potential maximum retention (S) as follows:

$$Q = (P - 0.2\ S)^2/(P + 0.8S) \quad \text{(Eq. S-7)}$$

Empirical studies indicate that S is a function of the curve number as follows:

$$S = (1000/CN) - 10 \quad \text{(Eq. S-8)}$$

Therefore, the runoff volume can be determined as a function of precipitation volume and curve number.

2.6.2 Soil Conservation Service Dimensionless Unit Hydrograph

To estimate the peak discharge and establish a runoff hydrograph in the SCS methods, the concept of a dimensionless unit hydrograph is applied. The SCS dimensionless unit hydrograph was derived from analysis of a large number of unit hydrographs developed using gage data from watersheds of a wide range in size and geographical location. The dimensionless unit hydrograph has ordinate values expressed in a dimensionless ratio q/q_p and abscissa values of t/T_p, where q_p is the peak discharge at time T_p and q is the discharge at time t. Figure 2-3 in Appendix B of this Manual shows the shape of the dimensionless unit hydrograph. At the same time, the mass curve is also illustrated in Figure 2-3 in Appendix B of this manual with coordinates of Q_a/Q vs t/t_p, in which Q_a is the accumulated volume at time t, and Q is the total volume. Table 2-11 lists dimensionless discharge ratios and mass curve ratios for dimensionless time ratios for use in calculating unit hydrographs and mass curves.

The curvilinear unit hydrograph can be approximated by an equivalent triangular unit hydrograph, as shown by dotted lines in Figure 2-3 in Appendix B of this Manual. The area under the rising limb (before time T_p) of the two (2) unit hydrographs are the same. The time base of the dimensionless unit hydrograph is five (5) times the time-to-peak (T_p), while the time base of the triangular unit hydrograph is only 2.67 times the time-to-peak (T_p). The transformation of curvilinear unit hydrograph to triangular unit hydrograph provides a solution for the peak flow.

A. **Derivation of Peak Flow.** The area under the triangular unit hydrograph on Figure 2-3 in Appendix B of this Manual equals the volume of direct runoff Q, which can be calculated by:

$$Q = q_p(T_p + T_r)/2 \quad \text{(Eq. S-9)}$$

where,

Q = Direct runoff, inches
T_p = Time to peak, hours
T_r = Recession time, hours
q_p = Peak discharge, inches per hour

The runoff Q derived from this equation is the same as estimated by Equation S-7.

By Equation S-9, the peak discharge q_p can be solved as:

$$q_p = 2Q/(T_p + T_r) \quad \text{(Eq. S-10)}$$

Let $$K = 2/(1 + (T_r/T_p)) \quad \text{(Eq. S-11)}$$

therefore, $$q_p = KQ/T_p \quad \text{(Eq. S-12)}$$

where, Q = Direct runoff, inches
T_p= Time to peak, hours
T_r= Recession time, hours
q_p= Peak discharge, inches per hour

In making the conversion from inches per hour to cubic feet per second and putting the equation in terms ordinarily used, including drainage area (A) in square miles, and time (T) in hours, equation S-12 becomes the general equation:

$$q_p = (645.33\ KAQ)/T_p \quad \text{(Eq. S-13)}$$

Where q_p is peak discharge in cubic feet per second and the conversion factor 645.33 is the rate required to discharge one (1) inch of excess rainfall from one (1) square mile in one (1) hour.

The relationship of the triangular unit hydrograph, shows that $T_r = 1.67\ T_p$ and gives K = 0.75 by Equation S-11. Then substituting into equation S-13 gives:

$$q_p = 484\ A\ Q/T_p \quad \text{(Eq. S-14)}$$

Since the volume under the rising side of the triangular unit hydrograph is equal to the volume under the rising side of the curvilinear dimensionless unit hydrograph in Figure 2-3 in Appendix B of this Manual, the constant 484, or peak rate factor, is valid for calculation of the peak discharge for the dimensionless unit hydrograph.

Table 2-11 Ratios for Soil Conservation Service Dimensionless Unit Hydrograph and mass Curve		
Time Ratios (t/T_p)	**Discharge Ratios (q/q_p)**	**Mass Curve Ratios (Q_a/Q)**
0.0	.000	.001
0.1	.030	.001
0.2	.100	.006
0.3	.190	.012
0.4	.310	.035
0.5	.470	.065
0.6	.660	.107
0.7	.820	.163
0.8	.930	.228
0.9	.990	.300
1.0	1.000	.375
1.1	.990	.450
1.2	.930	.522
1.3	.860	.589
1.4	.780	.650
1.5	.680	.700
1.6	.560	.751
1.7	.460	.790
1.8	.390	.822
1.9	.330	.849
2.0	.280	.871
2.2	.207	.908

Table 2-11 (Continued) Ratios for Soil Conservation Service Dimensionless Unit Hydrograph and mass Curve		
Time Ratios (t/T_p)	**Discharge Ratios (q/q_p)**	**Mass Curve Ratios (Q_a/Q)**
2.4	.147	.934
2.6	.107	.953
2.8	.077	.967
3.0	.055	.977
3.2	.040	.984
3.4	.029	.989
3.6	.021	.993
3.8	.015	.995
4.0	.011	.997
4.5	.005	.999
5.0	.000	1.000
Source: Soil Conservation Service. TR-55 Urban Hydrology for Small Watersheds.		