Module 10: Graphical Peak Discharge Method (TR-55)

Learning Objectives

At the end of this module, you will be able to:

- Estimate peak runoff discharge using the graphical peak discharge method (TR-55)
- Explain the factors associated with curve number determinations
- Verify assumptions made in the determination of curve numbers
- Calculate a weighted curve number
- Explain limitations of both graphical and tabular peak discharge methods

10a. Urban Hydrology for Small Watersheds (TR-55)

The NRCS published Technical Release Number 55 (TR-55): Urban Hydrology for Small Watersheds, 2nd edition, in June of 1986. The TR-55 method has since been developed into a Windows application available on the NRCS website along with a user guide. The 2009 user guide provides instructions to the application and updates to the original methodology introduced in 1986 (WinTR-55, 2009).

The TR-55 methodology allows the designer to manipulate the time distribution of the rainfall, the initial rainfall losses to interception and depression storage, and the moisture condition of the soils prior to the storm. The procedures developed by NRCS in TR-55 are based on a dimensionless rainfall distribution curve for a 24-hour storm.

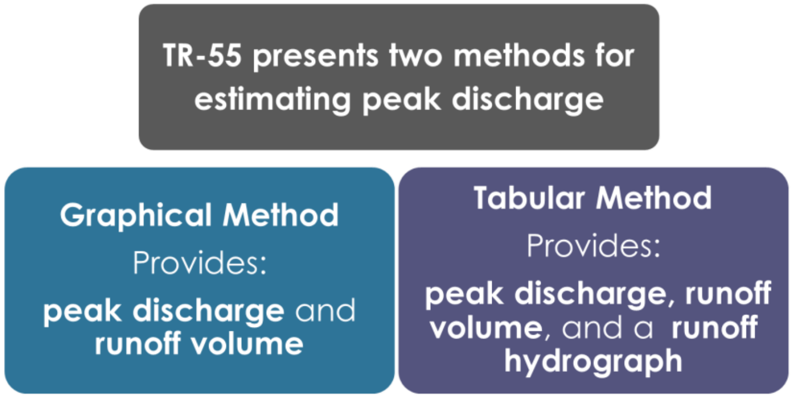
> The Natural Resources Conservation Service (NRCS) was previously known as the Soil Conservation Service (SCS). Some older published documents published may still reference SCS.

TR-55 presents two general methods for estimating peak discharges from urban watersheds: the graphical method and the tabular method. The graphical method is limited to watersheds whose runoff characteristics are fairly uniform and whose soils, land use, and ground cover can be represented by a single Runoff Curve Number (CN). The graphical method provides a peak discharge only and is not applicable for situations where a hydrograph is required.

The tabular method is a more complete approach and can be used to develop a hydrograph at any point in a watershed. It may be necessary to divide large areas into more than one sub-watershed to account for major land use changes, analyze specific study points within sub-watersheds, or locate stormwater drainage facilities and assess their effects on peak flows. The tabular method can generate a hydrograph for each sub-watershed for the same storm event. The hydrographs can then be routed through the watershed and combined to produce a partial composite hydrograph at the selected study point. The tabular method is particularly useful in evaluating the effects of an altered land use in a specific area within a given watershed.

Prior to using either the graphical or tabular methods, both the volume of runoff resulting from a given depth of precipitation and the time of concentration, T_c, for the watershed being analyzed, must be determined. The methods for determining these values were covered in Module 9 (9d. Estimating Runoff). The TR-55 graphical peak discharge method is covered in this module.

10b. TR-55 Peak Discharge Method



GRAPHICAL PEAK DISCHARGE METHOD (CHAPTER 4 OF TR-55)

The graphical peak discharge method was developed from hydrograph analyses using TR-20, Computer Program for Project Formulation-Hydrology (SCS, 1983). The graphical method develops the peak discharge in cubic feet per second (cfs) for a given watershed.

Graphical Peak Discharge Limitations

There are several limitations that the designer should be aware of before using the graphical peak discharge method:

1. The watershed being studied must be hydrologically homogeneous, i.e., the land use, soils, and cover are distributed uniformly throughout the watershed and can be described by one curve number.
2. The watershed may have only one main stream or flow path. If more than one is present they must have nearly equal T_cs so that the entire watershed is represented by one T_c.
3. The analysis of the watershed cannot be part of a larger watershed study, which would require adding hydrographs since the graphical method does not generate a hydrograph.
4. For the same reason, the graphical method should not be used if a runoff hydrograph is to be routed through a control structure.
5. When the initial abstraction/rainfall ratio (I_a/P) falls outside the range of the Unit Peak Discharge curves (0.1 to 0.5), the limiting value of the curve must be used.

6. The NRCS runoff procedures apply only to surface runoff and do not consider subsurface flow or high groundwater.

The reader is encouraged to review TR-55 documentation (1986 TR-55 Manual, Win-TR-55 User Guide, and the National Engineering Handbook(NEH)) to become familiar with these and other limitations associated with the graphical method.

The graphical method can be used as a planning tool to determine the impact of development or land use changes within a watershed, or to anticipate or predict the need for stormwater management facilities or conveyance improvements. Sometimes, the graphical method can be used in conjunction with the TR-55 short-cut method for estimating the storage volume required for post-developed peak discharge control. This short-cut method is found in Chapter 6 of TR-55 (1986) and is discussed later in this Participant Guide. More sophisticated computer models such as TR-20, HEC-HMS, or WinTR-55 Tabular Hydrograph Method, should be used for analyzing complex, urbanizing watersheds.

Graphical Peak Discharge Equation

The TR-55 Peak Discharge Equation is:

(Source: TR-55, Eq. 4-1)

$$q_p = q_u \times A_{mi} \times Q \times F_p$$

Peak Discharge Equation

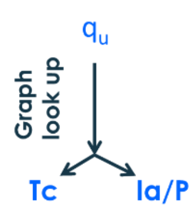
q_p = peak discharge (cfs)

q_u = unit peak discharge (cfs/mi^2/in or csm/in)

A_{mi} = drainage area (mi^2)

Q = runoff (in)

F_p = pond and swamp adjustment factor



$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

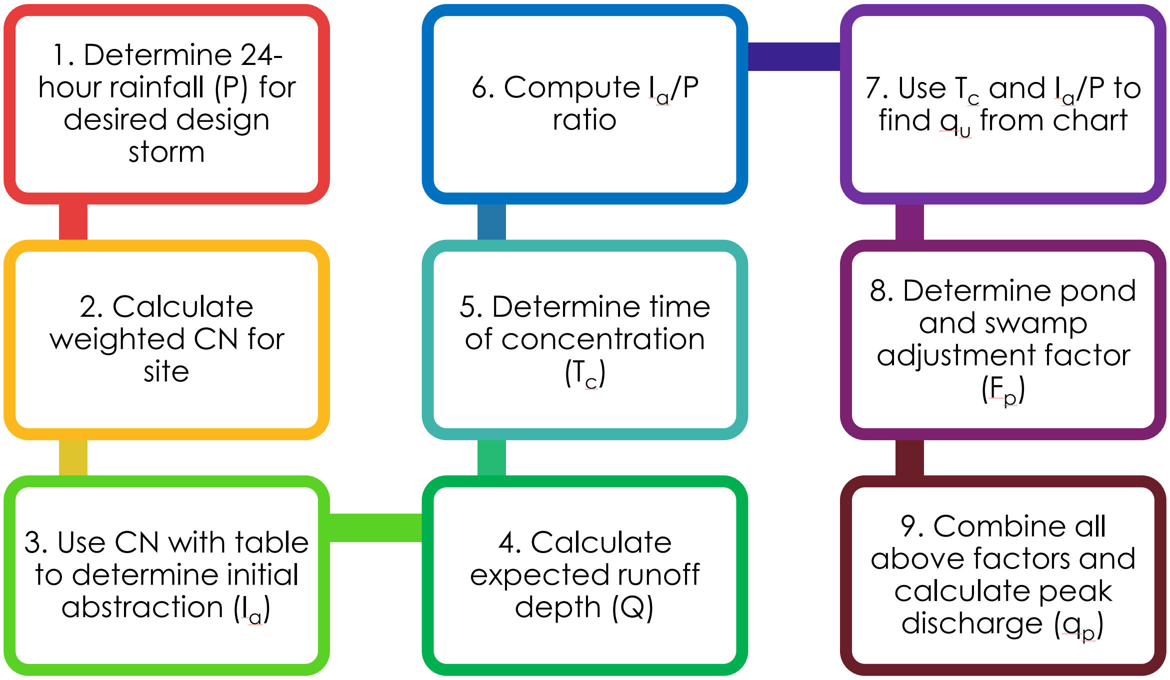
Q = Runoff (in)
P = Rainfall (in)
S = Potential maximum retention after runoff begins (in)

$$S = \left(\frac{1000}{CN}\right) - 10$$

CN = Curve number
I_a = Initial abstraction (in)
= 0.2 x S (all losses before runoff begins)

The steps required to determine all the necessary information as illustrated in the graphic above are detailed in the following sections of this Module.

Graphical Peak Discharge Procedure



The following represents a brief list of the parameters needed to compute the peak discharge of a watershed using the TR-55 Graphical Peak Discharge. For a more detailed explanation of the terms listed, refer to Chapter 3 of TR-55 (TR-55, 1986).

- Drainage area, in square miles (mi^2)
- Topography – detailed enough to accurately identify drainage divides, T_c and T_t flow paths, channel geometry, and surface condition (roughness coefficient).
- Time of Concentration, T_c , in hours (hr)
- Rainfall amount, P, for specified design storm, in inches (in)
- Total runoff, Q, in inches (in)
- Initial abstraction, I_a , for each subarea
- Ratio of I_a/P for each subarea
- Rainfall distribution type

1. Determine 24-hour rainfall (P) for desired design storm

Precipitation

- NOAA Atlas 14
- Distribution

1. Precipitation (rainfall)

NOAA Atlas 14, Volume 2, Version 3

Location name: Petersburg, Virginia, US*

Latitude: 37.1953°, Longitude: -77.3657°

POINT PRECIPITATION FREQUENCY ESTIMATES

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]							
Duration	**Average recurrence interval (years)**						
	1	**2**	**5**	**10**	**25**	**50**	**100**
10-min	0.616 (0.553-0.689)	0.727 (0.654-0.810)	0.845 (0.760-0.941)	0.951 (0.853-1.06)	1.07 (0.951-1.18)	1.16 (1.03-1.29)	1.24 (1.10-1.38)
15-min	0.770 (0.691-0.861)	0.913 (0.822-1.02)	1.07 (0.961-1.19)	1.20 (1.08-1.34)	1.35 (1.21-1.50)	1.46 (1.30-1.63)	1.57 (1.39-1.74)
30-min	1.06 (0.948-1.18)	1.26 (1.14-1.41)	1.52 (1.37-1.69)	1.74 (1.56-1.94)	2.00 (1.79-2.22)	2.21 (1.96-2.45)	2.40 (2.12-2.67)
60-min	1.32 (1.18-1.47)	1.58 (1.43-1.76)	1.95 (1.75-2.17)	2.27 (2.04-2.53)	2.66 (2.38-2.96)	2.99 (2.66-3.32)	3.31 (2.93-3.67)
2-hr	1.57 (1.40-1.76)	1.89 (1.69-2.11)	2.34 (2.10-2.62)	2.76 (2.47-3.08)	3.30 (2.93-3.67)	3.76 (3.32-4.18)	4.22 (3.70-4.69)
3-hr	1.69 (1.50-1.90)	2.03 (1.81-2.28)	2.52 (2.26-2.83)	2.99 (2.66-3.35)	3.58 (3.17-4.01)	4.09 (3.60-4.58)	4.63 (4.04-5.16)
6-hr	2.03 (1.81-2.31)	2.44 (2.17-2.76)	3.04 (2.70-3.43)	3.61 (3.19-4.07)	4.36 (3.84-4.91)	5.03 (4.39-5.64)	5.72 (4.96-6.41)
12-hr	2.42 (2.16-2.76)	2.91 (2.60-3.30)	3.64 (3.24-4.12)	4.35 (3.85-4.91)	5.32 (4.67-5.98)	6.19 (5.39-6.94)	7.11 (6.14-7.96)
24-hr	**2.80 (2.56-3.09)**	**3.40 (3.11-3.75)**	4.36 (3.98-4.81)	**5.17 (4.70-5.70)**	6.35 (5.74-6.99)	7.36 (6.61-8.10)	8.46 (7.54-9.30)

Figure 10-1: NOAA Atlas 14 Rainfall Depth Data for Petersburg, VA

2. Calculate weighted CN for site

2. Curve number (CN)

The CN is a measure of the land's ability to infiltrate or otherwise detain rainfall, with the excess becoming runoff. The CN is a function of the land cover (woods, pasture, agricultural use, percent impervious, etc.), hydrologic condition, and soils.

CN indicates runoff potential of an area

The data needed to solve the runoff equation and determine the watershed time of concentration, T_c, and travel time, T_t, are listed below. These items are discussed in more detail in TR-55 (Chapter 2).

- Soil information (to determine the Hydrologic Soil Group or HSG)
- Ground cover type (woods, meadow, open space, impervious area, etc.)
- Treatment (cultivated or agricultural land)
- Hydrologic condition (for design purposes, the hydrologic condition should be considered "GOOD" for the pre-developed condition)
- Antecedent runoff condition
- Urban impervious area modifications (connected, unconnected, etc.)

The NRCS Runoff Curve Number (CN) Method is used to estimate runoff. This method is described in detail in Chapter 9 of the NRCS National Engineering Handbook, Section 4 (210-VI-NEH, July 2004). The runoff equation (found in TR-55 and discussed later in this section) provides a relationship between runoff and rainfall as a function of the CN.

All four CN tables can be found in TR-55.

CN determination:

- Soils
- Hydrologic conditions (good, fair, poor)
- Cover type
- Treatment (agricultural lands)

4 Curve Number Tables

- Urban
  Cover Type – vegetation, bare soil, and impervious surfaces
- Cultivated agricultural lands
- Other agricultural lands
- Arid and semiarid rangelands
- Treatment
  - Cover type modifier for agricultural (contouring, terracing)
  - For agricultural and arid/semiarid

2. Calculate weighted CN for site

CN Limitations

1. TR-55 has simplified the relationship between rainfall and runoff by reducing all of the initial losses before runoff begins, or initial abstraction (I_a), and approximating the soil and cover conditions using the storage variable, S, potential maximum retention. Both of these terms, I_a and S, are functions of CN.

   A CN describes average conditions that are useful for design purposes. If the purpose of the hydrologic study is to model a historical storm event, average conditions may not be appropriate.

2. I_a represents interception, initial infiltration, surface depression storage, evapotranspiration, and other watershed factors and is generalized as a function of the runoff curve number based on data from agricultural watersheds.

   This can be especially important in an urban application because the combination of impervious area with pervious area can imply a significant initial loss that may not take place. On the other hand, the combination of impervious and pervious area can underestimate initial losses if the urban area has significant surface depression storage.

3. Runoff from snowmelt or frozen ground cannot be estimated using these procedures.

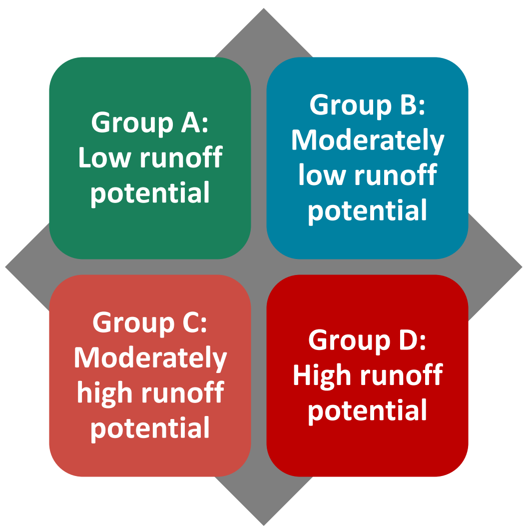
4. The CN method is less accurate when the runoff is less than 0.5 inch. As a verification, another procedure should be used to determine runoff.

2. Calculate weighted CN for site

Hydrologic Soil Groups

In hydrograph applications, runoff is often referred to as rainfall excess or effective rainfall and is defined as the amount of rainfall that exceeds the land's capability to infiltrate or otherwise retain the rainwater. The soil type or classification, the land use and land treatment, and the hydrologic condition of the cover are the watershed factors that will have the most significant impact on estimating the volume of rainfall excess, or runoff.

By using information obtained from local NRCS offices, soil and water conservation district offices, or from NRCS Soil Surveys (published for many counties across the country), the soils in a given area can be identified. Preliminary soil identification is useful for watershed analysis and planning in general. ***When preparing a plan for a specific site, it is recommended that soil borings be taken to verify the hydrologic soil classification.***



Appendix A of TR-55 provides a table for determining HSG for disturbed or unmapped soils based upon the soil texture as classified from field and laboratory investigation (see Figure 10-2 below).

HSG	*Soil textures*
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

Figure 10-2: HSG Based Upon Soil Texture for Disturbed Soils (TR-55, 1986)

2. Calculate weighted CN for site

Hydrologic Conditions

Hydrologic condition represents the effects of cover type and treatment on infiltration and runoff. It is generally estimated from the density of plant and residue cover across the drainage area. Good hydrologic condition indicates that the cover has a low runoff potential, while poor hydrologic condition indicates that the cover has a high runoff potential.

Hydrologic condition is used in describing non-urbanized lands such as woods, meadow, brush, agricultural land, and open spaces associated with urbanized areas, such as lawns, parks, golf courses, and cemeteries. Treatment is a cover type modifier to describe the management of cultivated agricultural lands.

When a watershed is being analyzed to determine the impact of proposed development, Virginia's water quantity technical criteria (9VAC25-875-600.E) require the designer to consider all existing or undeveloped land to be in hydrologically good condition. This results in lower existing condition peak runoff rates that, in turn, results in greater post-development peak control. In most cases, undeveloped land is in good hydrologic condition unless it has been altered in some way. Since the goal of most stormwater programs is to reduce the peak flows from developed or altered areas to their pre-developed or pre-altered rates, this is a reasonable approach. In addition, this approach eliminates any inconsistencies in judging the condition of undeveloped land or open space.

Runoff Curve Number (CN) Determination

The hydrologic soil group classification, cover type, and the hydrologic condition are used to determine the runoff curve number, CN. The CN indicates the runoff potential of an area when the ground is not frozen. Figure 10-3 and Figure 10-4 on the following pages (Tables 2-2a and 2-2c from TR-55, 1986) provide the CNs for various land use types and soil groups. All four CN tables can be found in TR-55.

Several factors should be considered in the selection of a CN for a given land use. The curve numbers in TR-55 represent the ***average antecedent runoff or moisture condition, ARC***. The ARC is the index of runoff potential before a storm event and can have a major impact on the relationship between rainfall and runoff for a watershed. Average ARC implies that the soils are neither very wet nor very dry when the design storm begins. Average ARC runoff curve numbers can be converted to dry or wet values; however, the average antecedent runoff condition is recommended for design purposes.

2. Calculate weighted CN for site

Table 2-2a Runoff curve numbers for urban areas 1/

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area 2/	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) 3/:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) 4/		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
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) 5/		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

1 Average runoff condition, and $I_a = 0.2S$.
2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Figure 10-3: Runoff Curve Numbers for Urban Areas (TR-55, 1986)

2. Calculate weighted CN for site

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover type	Hydrologic condition	A	B	C	D
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	30 [4]	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	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

Cover description; Curve numbers for hydrologic soil group (A–D).

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 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
6 *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.

Figure 10-4: Runoff Curve Numbers for Other Agricultural Lands (TR-55, 1986)

Figure 10-5 shows the decision-making process for analyzing a drainage area. The flow chart can be used to select the appropriate tables or figures in TR-55 for runoff curve numbers (Figure 10-6 and Figure 10-7 discussed in the next sections). Worksheet 2 of TR-55 (see Figure 10-8) is then used to compute the weighted curve number for the area or subarea.

2. Calculate weighted CN for site

CN Assumptions

It is also important to consider the list of assumptions made in developing the runoff curve numbers as provided in TR-55. Some of these assumptions are outlined below:

1. The urban CNs, for such land uses as residential, commercial, and industrial, are computed with the percentage of impervious area as shown. A ***composite curve number*** should be re-computed using the actual percentage of imperviousness if it differs from the value shown.
2. The impervious areas are ***directly connected*** to the drainage system.
3. ***Impervious areas*** have a runoff curve number of 98.
4. Pervious areas are considered equivalent to open space in good hydrologic condition.
5. These assumptions, as well as others, are footnoted in Tables 2-2a to 2-2d of TR-55 (TR-55, 1986). TR-55 provides a graphical solution for modification of the given CNs if any of these assumptions do not hold true.
6. Experience and professional judgement, as well as familiarity with appropriate application of graphical solutions relating to refinement of CN for connected versus unconnected impervious areas, is required to make field evaluations of the various criteria used in the determination of the CN for a given site.

Additional Considerations:

A watershed can contain sufficient diversity in land use to justify dividing the watershed into several ***sub-watersheds***. When ***one weighted curve number*** cannot adequately describe a watershed or drainage area:

- the watershed should be divided into subareas
- each subarea should be analyzed individually
- individual hydrographs should be generated for each subarea
- the individual hydrographs should be added together to determine the composite peak discharge for the entire watershed

2. Calculate weighted CN for site

Connected vs Unconnected Impervious Area

The percentage of impervious area and the conveyance system from an impervious area to the drainage system should be considered in computing CN for urban areas. An impervious area is considered ***connected*** if runoff from it flows directly into the drainage system. It is also considered connected if runoff from it occurs as ***concentrated shallow flow*** that runs over a pervious area and then into the drainage system.

Connected impervious area:

- Runoff flows directly to drainage system; or
- Runoff is **concentrated shallow flow** over pervious area and then into drainage system

Unconnected impervious area:

- Runoff from impervious area is spread over pervious area as **sheet flow** before discharging to drainage system

Urban CN's developed for TR-55 land uses are based on assumed percentages of impervious area.

The CN values were developed assuming pervious urban areas are comparable to pasture in good condition, while impervious areas are directly connected to the drainage system with a CN of 98. Assumed percentages of impervious area are provided in Table 2-2a of TR-55 as reproduced earlier in Figure 10-3. If all the impervious area is directly connected to the drainage system, but the impervious area percentages or the pervious land use assumptions are not applicable, then the designer may use Figure 2-3 of TR-55 (see Figure 10-6) to compute a composite CN.

Connected vs. unconnected

Total impervious area < 30% and Impervious area not directly connected
Use Figure 2-4 of TR-55 to determine CN (see Figure 10-7)

Total impervious area ≥ 30%
Impervious area considered connected
Use Figure 2-3 from TR-55 to adjust CN (see Figure 10-6)

Other considerations apply if runoff from ***unconnected*** (or disconnected) impervious areas is spread over a pervious area as ***sheet flow*** before discharging to the drainage system. When all or part of the impervious area is not directly connected, the designer may use the graphs in

2. Calculate weighted CN for site

Figure 10-7 (Figure 2-4 of TR-55) to determine the CN, provided the total impervious area is less than 30 percent. If the total impervious area is ≥ 30%, Figure 10-6 (Figure 2-3 from TR-55) may be used to adjust the CN, because the absorptive capacity of the remaining pervious areas will not significantly affect runoff.

Disconnecting runoff from impervious areas is an important design component of ***Stormwater Site Design*** and can provide ***Runoff Reduction***, as discussed in Module 5 of this Participant Guide and in the Plan Reviewer for Stormwater Management Participant Guide.

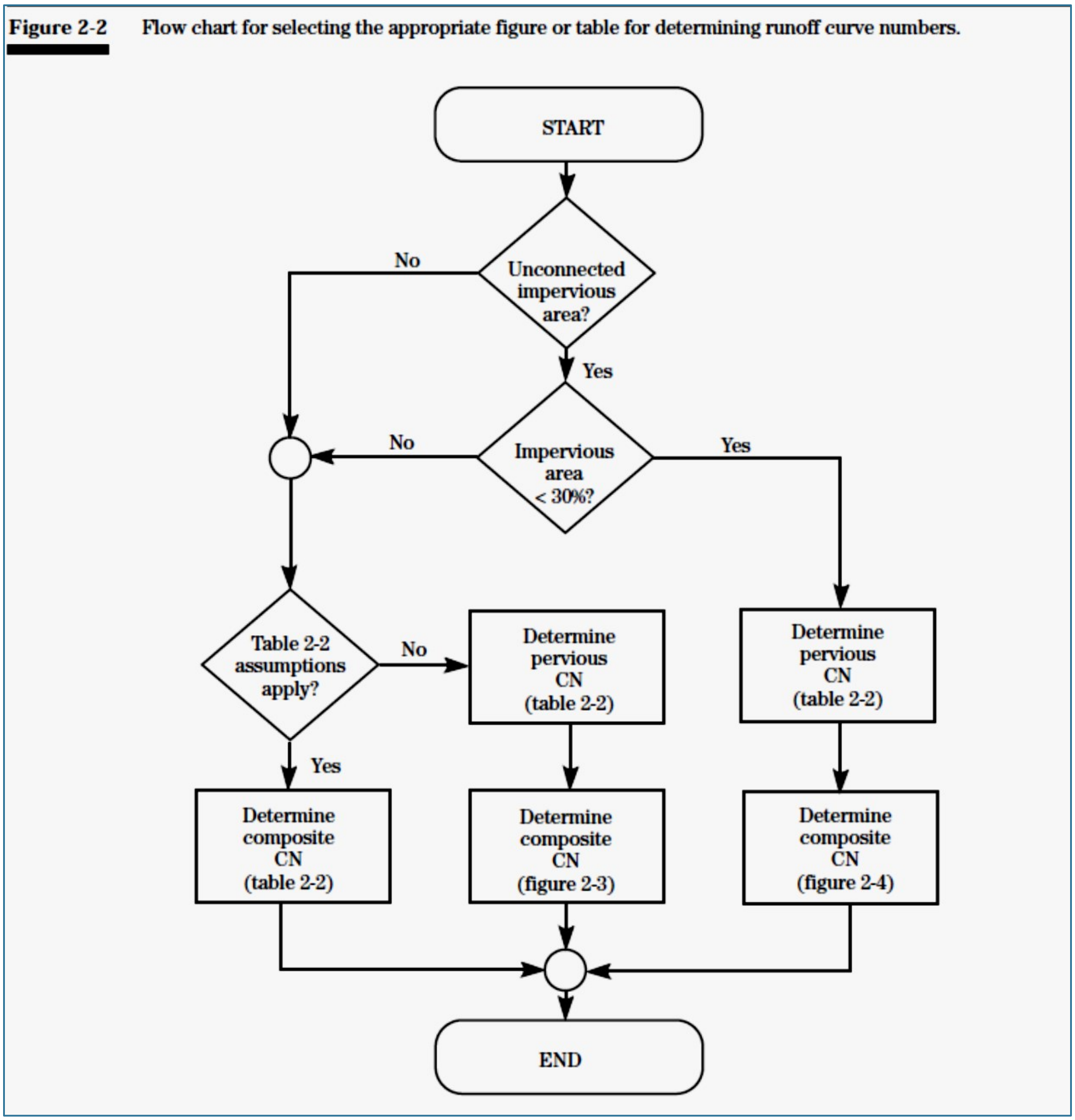


Figure 10-5: Flow Chart for Determining Runoff Curve Number (CN) (TR-55, 1986)

2. Calculate weighted CN for site

Figure 2-3 Composite CN with connected impervious area.

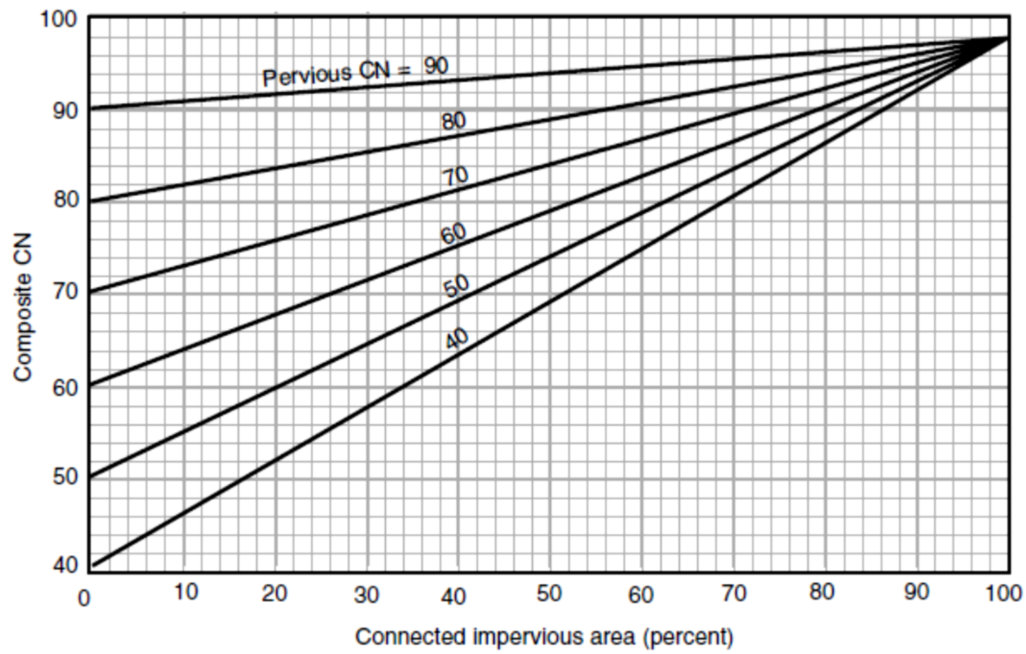


Figure 10-6: Composite CN with Connected Impervious Area or Impervious Area or Impervious Area ≥ 30% of Drainage Area (TR-55, 1986)

Figure 2-4 Composite CN with unconnected impervious areas and total impervious area less than 30%

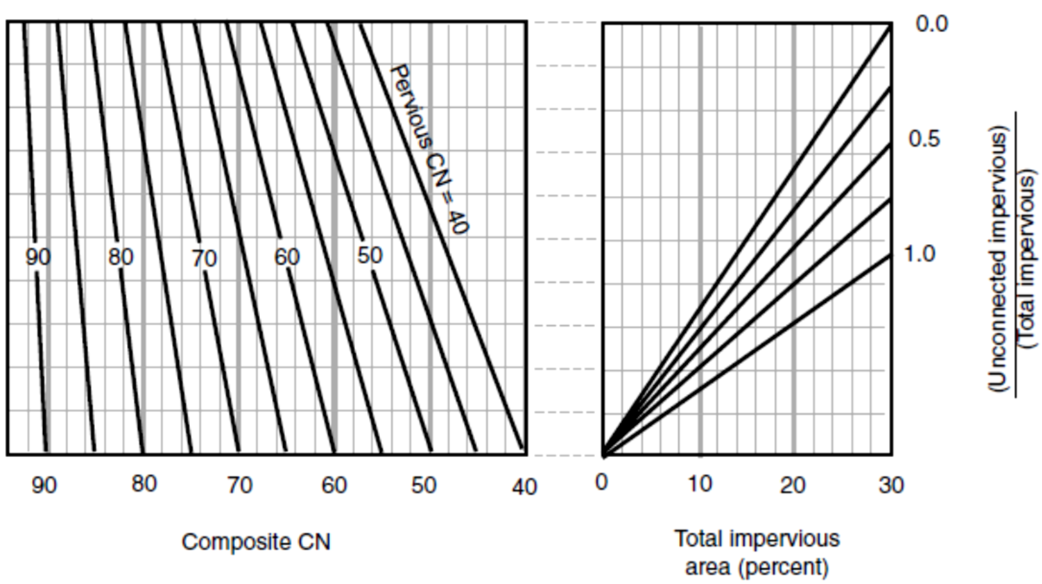


Figure 10-7: Composite CN with Unconnected Impervious Area and Total Impervious Area <30% (TR-55, 1986)

2. Calculate weighted CN for site

Worksheet 2: Runoff curve number and runoff

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN [1] Table 2-2	CN [1] Figure 2-3	CN [1] Figure 2-4	Area ☐ acres ☐ mi^2 ☐ %	Product of CN x area
				Totals ➡		

[1] Use only one CN source per line

CN (weighted) = $\frac{\text{total product}}{\text{total area}}$ = ______________ = ________ ; Use CN ➡ ☐

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr			
Rainfall, P (24-hour)	in			
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in			

Figure 10-8: Worksheet 2 Runoff Curve Number and Runoff (TR-55, 1986)

3. Initial abstraction (I_a)

The initial abstraction is a measure of all the losses that occur before runoff begins, including infiltration, evaporation, depression storage, and water intercepted by vegetation, and can be calculated from empirical equations or Figure 10-9 on the next page (Table 4-1 from TR-55, 1986). The initial abstraction is calculated from the curve number.

I_a can also be calculated using the following equation:

$$I_a = 0.2 \times \left[\left(\frac{1000}{CN}\right) - 10\right]$$

(TR-55 Eq. 2-2 and TR-55 Eq. 2-4 combined)

CN = Runoff Curve Number

Table 4-1 I_a values for runoff curve numbers

Curve number	I_a (in)	Curve number	I_a (in)
40	3.000	70	0.857
41	2.878	71	0.817
42	2.762	72	0.778
43	2.651	73	0.740
44	2.545	74	0.703
45	2.444	75	0.667
46	2.348	76	0.632
47	2.255	77	0.597
48	2.167	78	0.564
49	2.082	79	0.532
50	2.000	80	0.500
51	1.922	81	0.469
52	1.846	82	0.439
53	1.774	83	0.410
54	1.704	84	0.381
55	1.636	85	0.353
56	1.571	86	0.326
57	1.509	87	0.299
58	1.448	88	0.273
59	1.390	89	0.247
60	1.333	90	0.222
61	1.279	91	0.198
62	1.226	92	0.174
63	1.175	93	0.151
64	1.125	94	0.128
65	1.077	95	0.105
66	1.030	96	0.083
67	0.985	97	0.062
68	0.941	98	0.041
69	0.899		

Figure 10-9: Initial Abstraction Values for Runoff Curve Numbers (TR-55, 1986)

4. Runoff depth (Q)

The NRCS Runoff Equation is used to solve for runoff as a function of the initial abstraction, I_a, and the potential maximum retention, S, of a watershed. Both are functions of the CN. This equation attempts to quantify the losses before runoff begins, including infiltration, evaporation, depression storage, and water intercepted by vegetation. The runoff computed with the Runoff Equation is a fraction of the rainfall, generally reported in inches.

The Runoff Equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

(Source: TR-55, Eq. 2-1)

Runoff Equation

Q = runoff, inches (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in)

$$S = \frac{1000}{\text{CN}} - 10$$

(Source: TR-55, Eq. 2-4)

CN = runoff curve number
I_a = initial abstraction (in) = 0.2 x S (Source: TR-55, Eq. 2-2)

By substituting the product (0.2 x S) for the term I_a, the Runoff Equation can be simplified to:

$$Q = \frac{(P - 0.2 \times S)^2}{(P + 0.8 \times S)}$$

(Source: TR-55, Eq. 2-3)

Runoff Equation (Simplified)

4. Runoff depth (Q)

TR-55 also provides a graphical solution and tabular solution for the runoff equation. The graphical solution is found in Chapter 2 of TR-55 and is reproduced below in Figure10-10. The tabular solution is reproduced below in Figure 10-11. Both the equation and graphical solution solve for the depth of runoff that can be expected from a watershed or sub-watershed, of a specified CN, for any given frequency storm. Additional information can be found in the NRCS National Engineering Handbook, Section 4. These procedures, by providing the basic relationship between rainfall and runoff, are the basis for any hydrological study based on NRCS methodology.

Figure 2-1 Solution of runoff equation.

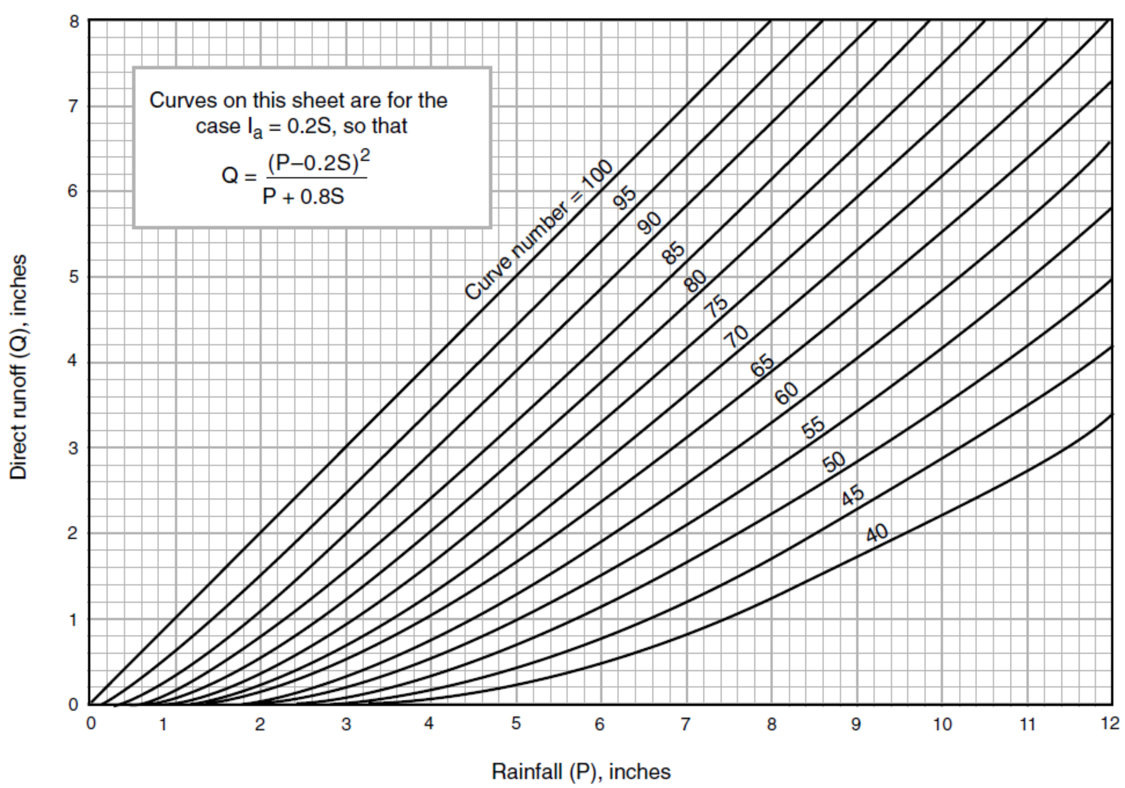


Figure10-10: Graphical Solution to the Runoff Equation (TR-55, 1986)

Example 10-1:

For a given watershed with a CN of 80, what is the direct runoff (Q) from a rainfall (P) of 4.0 in.?

Step 1: Find rainfall depth of 4.0 inches on x-axis and draw line (Line 1) perpendicular to x-axis

Step 2: Find curve for CN = 80 and locate where Line 1 intersects curve for CN = 80

Step 3: Starting at intersection of Line 1 and curve CN = 80, draw line parallel to x-axis until it crosses y-axis (Line 2)

Step 4: Where Line 2 crosses y-axis, read value for Q. For this example, Q = 2.0 inches.

4. Runoff depth (Q)

Table 2-1 Runoff depth for selected CN's and rainfall amounts [1/]

Rainfall	Runoff depth for curve number of—												
	40	45	50	55	60	65	70	75	80	85	90	95	98
	inches												
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	.27	.46	.74	.99
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
4.5	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
7.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

[1/] Interpolate the values shown to obtain runoff depths for CN's or rainfall amounts not shown.

Figure 10-11: Tabular Solution to the Runoff Equation (TR-55, 1986)

Example 10-2:

For a given watershed with a CN of 80, what would be the direct runoff (Q) from a rainfall (P) of 4.0 inches?

Step 1: Find rainfall depth of 4.0 in the first column and draw a horizontal Line 1 to the right

Step 2: Find CN = 80 in the second row and draw a vertical Line 2 down

Step 3: Where Line 1 and Line 2 intersect, read the value for Q. For this example, Q = 2.04 inches.

7. Use T_c and I_a/P to find q_u from chart

5. Time of concentration and travel time (Chapter 3 of TR-55)

The time of concentration, T_c, is discussed in Module 9. Similar to the rational method, the time of concentration, T_c, plays an important role in developing the peak discharge for a watershed.

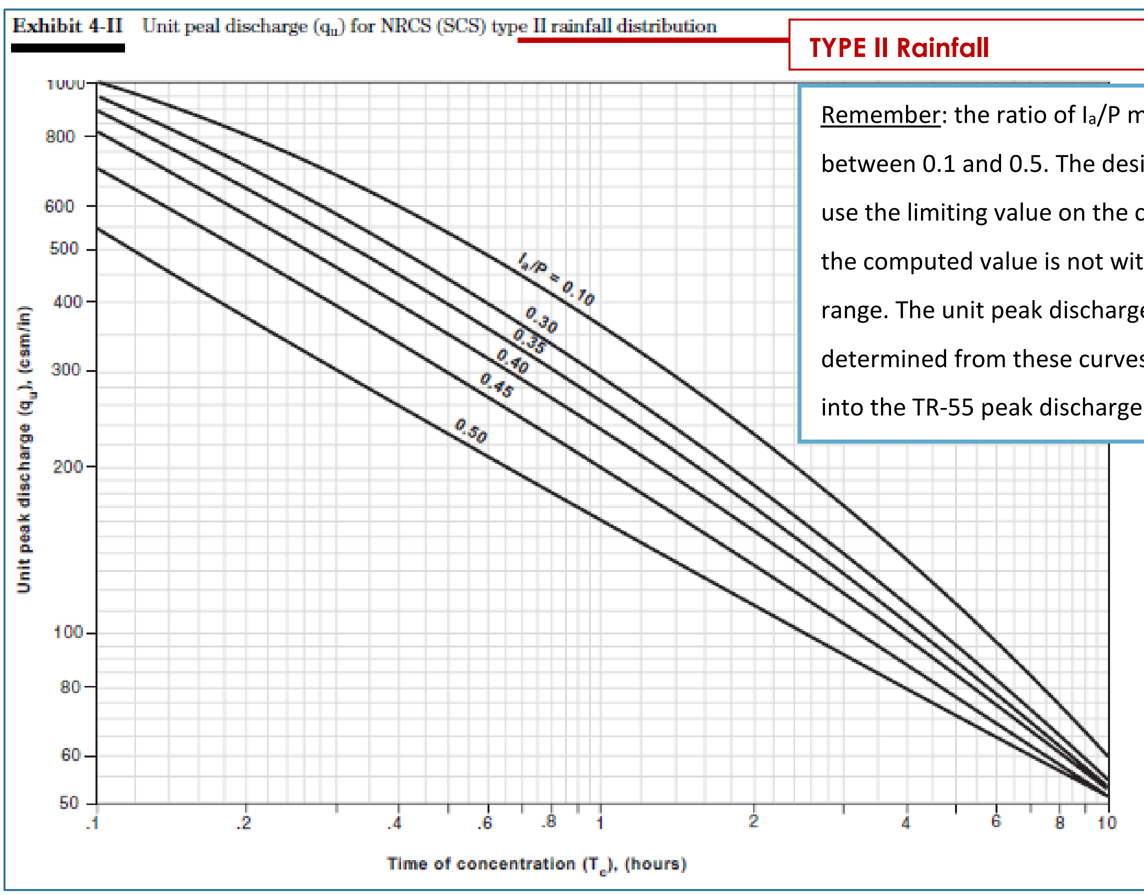
6. Compute I_a/P ratio

Use the initial abstraction (I_a) obtained in step 3 and the precipitation (P) determined in step 1.

7. Unit peak discharge (q_u)

Find q_u on chart:

1. Use I_a and P to calculate I_a/P ratio
2. Use ratio and T_c value to find q_u from chart



Remember: the ratio of I_a/P must fall between 0.1 and 0.5. The designer must use the limiting value on the curves when the computed value is not within this range. The unit peak discharge is determined from these curves and entered into the TR-55 peak discharge equation.

Figure 10-12: Unit Peak Discharge (q_u) for Type II Rainfall Distribution (TR55, 1986)

7. Use T_c and I_a/P to find q_u from chart

The ***unit peak discharge (q_u)*** is a function of the initial abstraction (I_a), precipitation (P), and the time of concentration (T_c) and can be determined from the Unit Peak Discharge Curves in TR-55. The unit peak discharge is expressed in cubic feet per second per square mile per inch of runoff (cfs/mi²/in or csm/in).

The unit peak discharge, q_u, is obtained by using T_c and the I_a/P ratio with Exhibit 4-I, 4-IA, 4-II, or 4-III (depending on the rainfall distribution type) in TR-55 (1986). Exhibit 4-II (reproduced in Figure 10-12) is used for most 24-hour rainfall distributions in Virginia, except for a portion of southeastern Hampton Roads where Exhibit 4-III (Figure 10-13) applies (portions of the Cities of Chesapeake, Norfolk, Portsmouth, Suffolk, and Virginia Beach).

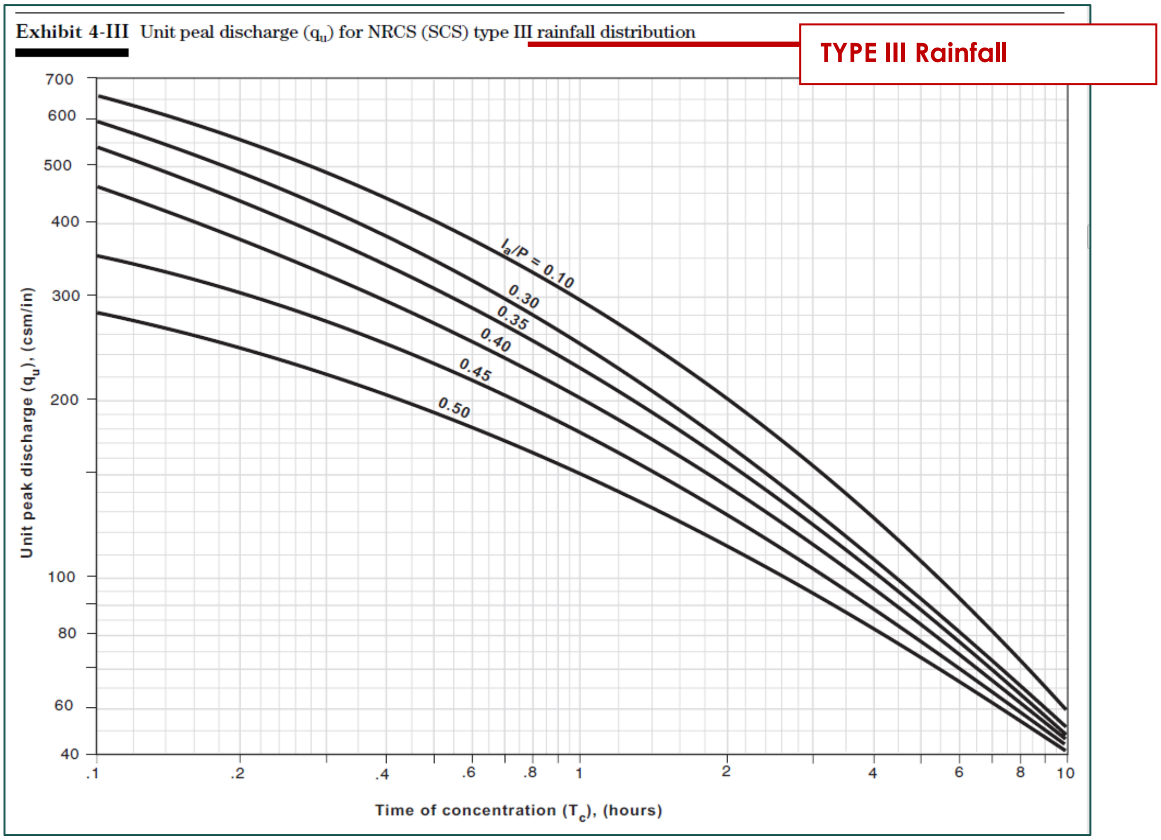


Figure 10-13: Unit Peak Discharge (q_u) for Type III Rainfall Distribution (TR55, 1986)

7. Use T_c and I_a/P to find q_u from chart

Since NRCS Type II Rainfall distributions no longer match NOAA Atlas 14 rainfall data, the newer NOAA rainfall distribution types, unit peak discharge curves have been updated for Virginia (NEH Part 650 Engineering Field Handbook, Chapter 2, Appendix VA650.29-4). Rainfall Distribution Type Equations, Peak Discharge Curves, and Peak Discharge Equation Coefficients:

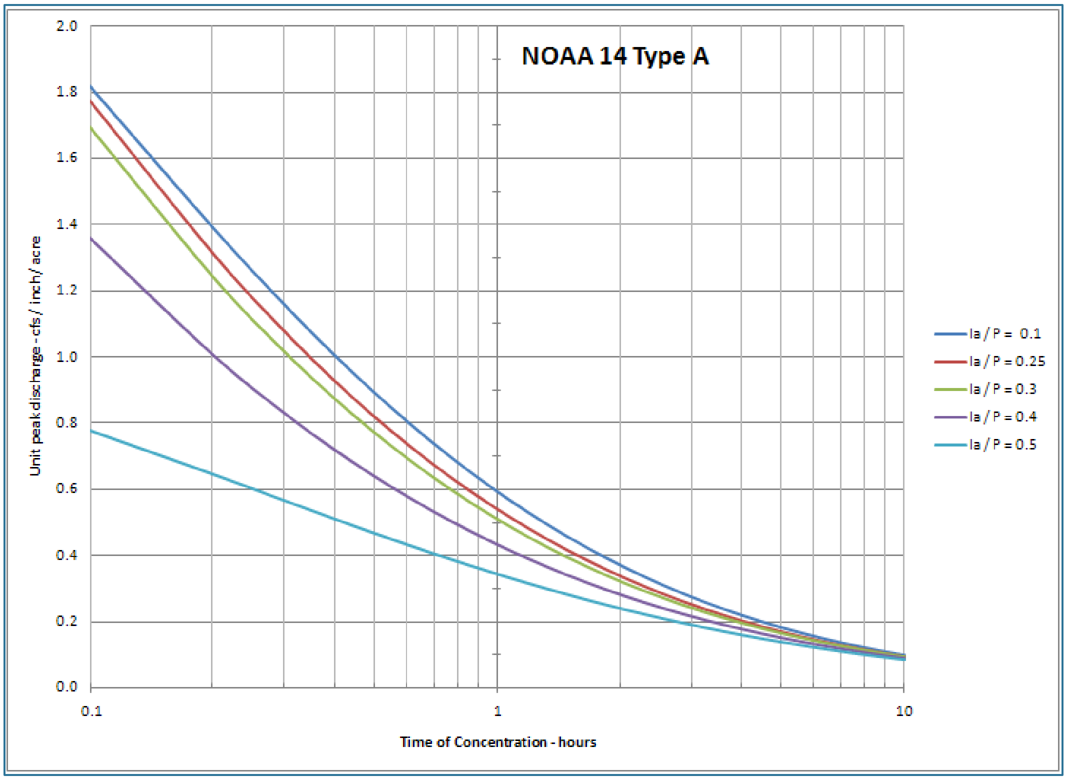


Figure 10-14: NOAA 14 Type A - Unit Peak Discharge Curve

7. Use T_c and I_a/P to find q_u from chart

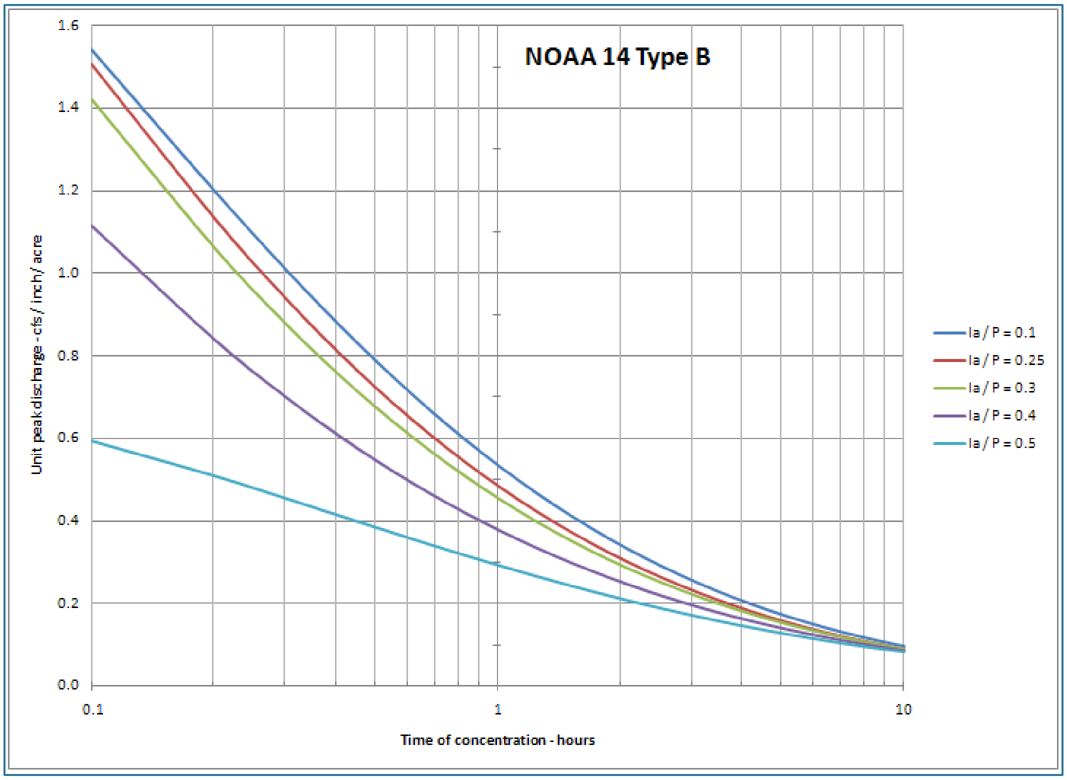


Figure 10-15: NOAA 14 Type B - Unit Peak Discharge Curve

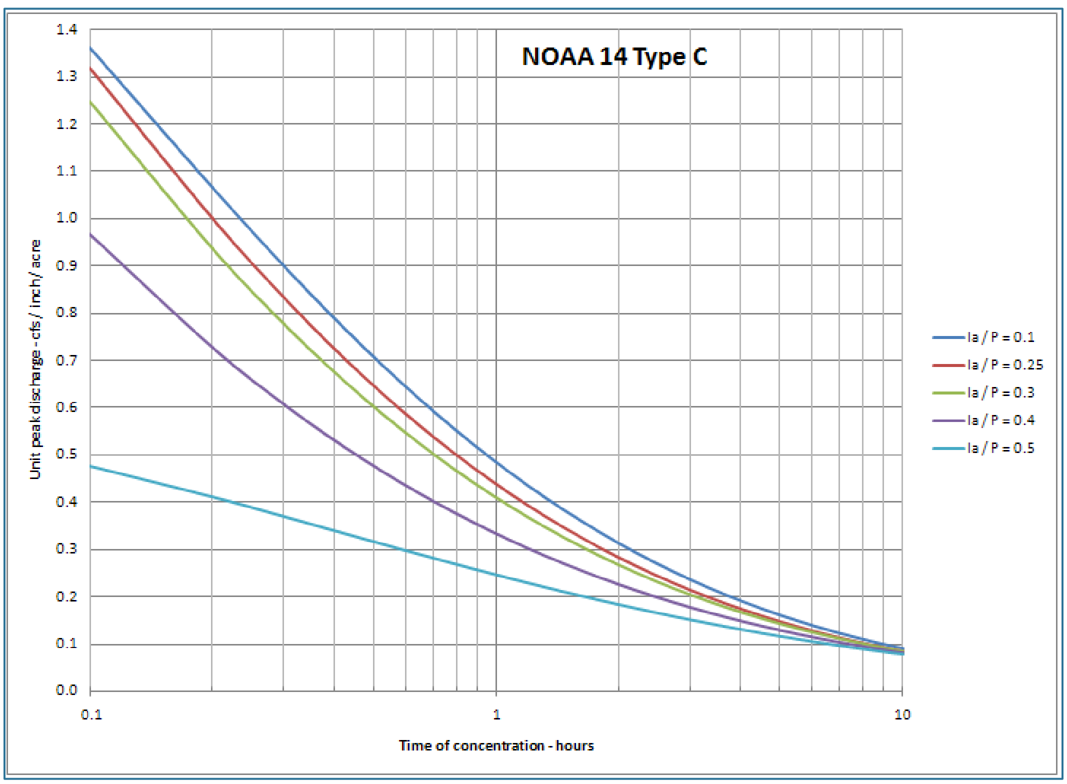


Figure 10-16: NOAA 14 Type C - Unit Peak Discharge Curve

7. Use T_c and I_a/P to find q_u from chart

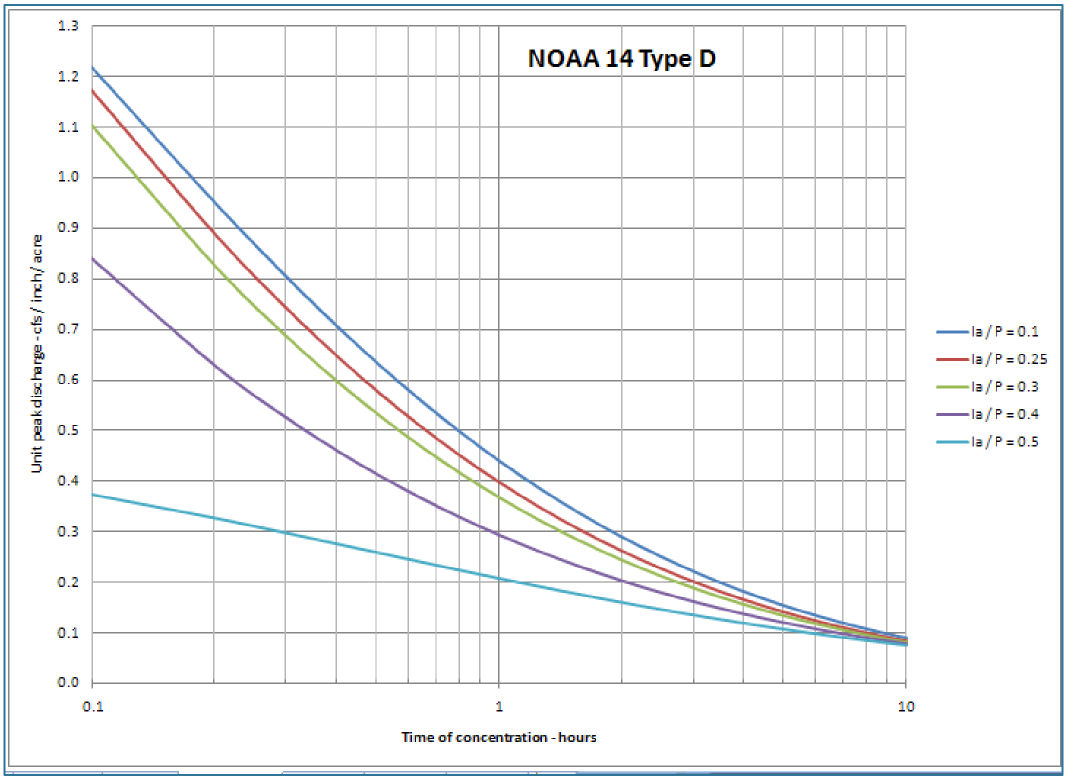


Figure 10-17: NOAA 14 Type D - Unit Peak Discharge Curve

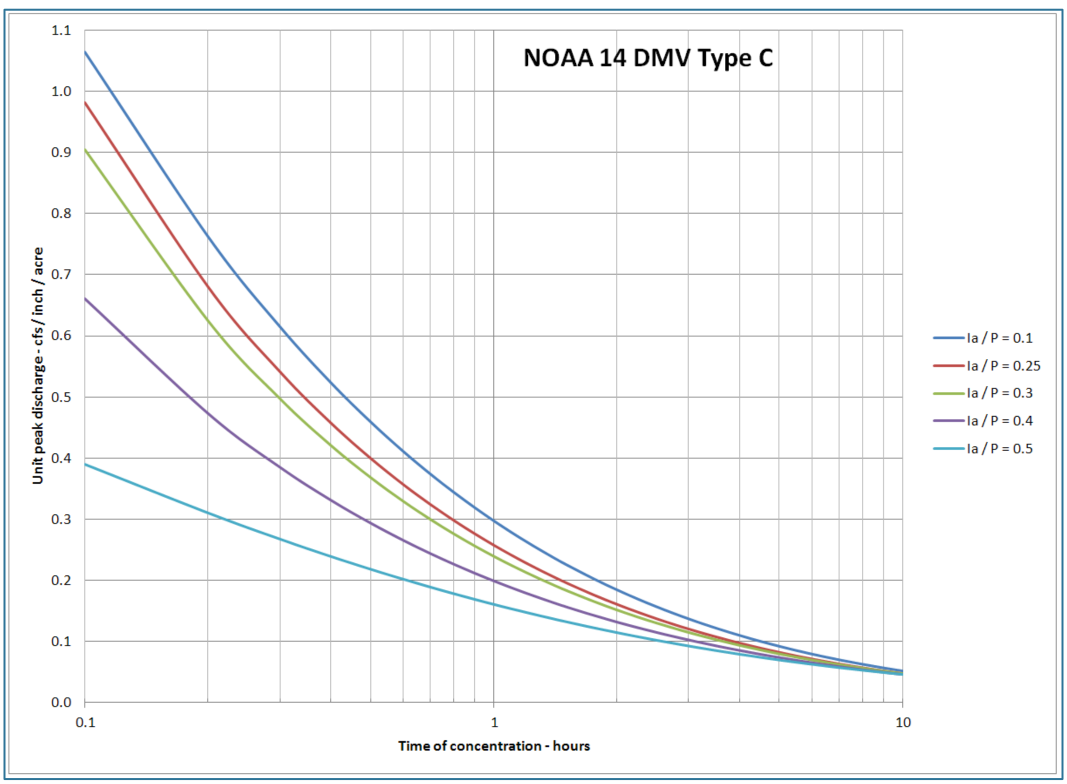


Figure 10-18: NOAA 14 DMV Type C - Unit Peak Discharge Curve

8. Determine pond and swamp adjustment factor (F_p)

8. Pond/swamp adjustment factor (F_p)

Table 4-2 Adjustment factor (F_p) for pond and swamp areas that are spread throughout the watershed

Percentage of pond and swamp areas	F_p
0	1.00
0.2	0.97
1.0	0.87
3.0	0.75
5.0	0.72

Figure 10-19: Pond and Swamp Adjustment Factor (TR-55, 1986)

The **pond and swamp adjustment factor (F_p)** is an adjustment in the peak discharge to account for pond and swamp areas if they are spread throughout the watershed and are not considered in the T_c computation. Refer to TR-55 (1986) for more information on pond and swamp adjustment factors. The pond and swamp adjustment factor (F_p) is determined using Table 4-2 of TR-55 (reproduced above in Figure 10-19).

9. Combine all and calculate peak discharge (q_p)

9. Calculate peak discharge (q_p)

$$q_p = q_u \times A_{mi} \times Q \times F_p$$

TR-55 Peak Discharge Equation

q_p = peak discharge (cfs)
q_u = unit peak discharge (cfs/mi^2/in or csm/in) *
A_{mi} = drainage area (mi^2) *
Q = runoff (in)
F_p = pond and swamp adjustment factor

(Source: TR-55, Eq. 4-1)

* If qu (cfs/in/acre) is derived using unit peak discharge curves with NOAA Atlas 14 rainfall distributions, substitute area (A) in acres for area (A_{mi}) in square miles.

Worksheet 4 from TR-55 (see Figure 10-20 on the next page) provides a succinct and organized format for documenting inputs and calculating the results for the graphical peak discharge method.

9. Combine all and calculate peak discharge (q_p)

Worksheet 4: Graphical Peak Discharge method

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed

1. Data

Drainage area .... A_m = ______________ mi^2 (acres/640)

Runoff curve number ....CN = ______________ (From worksheet 2)

Time of concentration .... T_c = ______________ hr (From worksheet 3)

Rainfall distribution .... = ______________ (I, IA, II III)

Pond and swamp areas sprea throughout watershed .... = ____________ percent of A_m (________ acres or mi^2 covered)

		Storm #1	Storm #2	Storm #3
2. Frequency	yr			
3. Rainfall, P (24-hour)	in			
4. Initial abstraction, I_a (Use CN with table 4-1)	in			
5. Compute I_a/P				
6. Unit peak discharge, q_u (Use T_c and I_a/P with exhibit 4– _____)	csm/in			
7. Runoff, Q (From worksheet 2) Figure 2-6	in			
8. Pond and swamp adjustment factor, F_p (Use percent pond and swamp area with table 4-2. Factor is 1.0 for zero percent pond ans swamp area.)				
9. Peak discharge, q_p	ft^3/s			

(Where $q_p = q_u A_m Q F_p$)

Figure 10-20: Worksheet 4 Graphical peak Discharge Method (TR-55, 1986)

10c. Tabular Hydrograph Method

The tabular hydrograph method (Chapter 5 of TR-55) can be used to analyze large heterogeneous watersheds. The tabular method can develop partial composite flood hydrographs at any point in a watershed by dividing the watershed into homogeneous subareas. The method is especially applicable for estimating the effects of land use change in a portion of a watershed. The tabular hydrograph method provides a tool to efficiently analyze several sub-watersheds to verify the combined impact at a downstream study point. It is especially useful to verify the timing of peak discharges. Sometimes, the use of detention in a lower sub-watershed may actually increase the combined peak discharge at the study point. This procedure allows a quick check to verify the timing of the peak flows and to decide if a more detailed study is necessary.

TABULAR HYDROGRAPH LIMITATIONS

The following represents some of the basic limitations that the designer should be aware of before using the TR-55 tabular method:

1. The travel time, T_t , must be less than 3 hours
2. The time of concentration, T_c , must be less than 2 hours
3. The acreage of the individual sub-watersheds should not differ by a factor of 5 or more.

When these limitations cannot be met, the designer should use the TR-20 computer program or other available computer models that will provide more accurate and detailed results. The TR-55 documentation should be referenced for more information on these and other limitations associated with the tabular method.

TABULAR HYDROGRAPH INFORMATION NEEDED

The following represents a brief list of the parameters needed to compute the peak discharge of a watershed using the TR-55 Tabular method. For a detailed explanation of the terms listed, refer to TR-55 (1986).

- Subdivision of the watershed into areas that are relatively homogeneous.
- The drainage area of each subarea, in square miles.
- Time of concentration, T_c , for each subarea in hours.
- Travel time, T_t , for each routing reach, in hours.
- Weighted runoff curve number, CN, for each subarea.
- Rainfall amount, P, in inches, for each specified design storm.
- Total runoff, Q, in inches (see runoff equation, TR-55) for each subarea.
- Initial abstraction, I_a , for each subarea.
- Ratio of I_a/P for each subarea.
- Rainfall distribution (I, IA, II, or III) or NOAA Atlas 14 distributions.

TABULAR HYDROGRAPH DESIGN PROCEDURE

The use of the tabular method requires that the designer determine the travel time through the entire watershed. As stated previously, the entire watershed is divided into smaller sub-watersheds that must be related to one another and to the whole watershed with respect to time. The result is that the time of peak discharge is known for any one sub-watershed relative to any other sub-watershed or for the entire watershed. Travel time, T_t, represents the time for flow to travel from the study point at the bottom of a sub-watershed to the bottom of the entire watershed. This information must be compiled for each sub-watershed.

To obtain the peak discharge using the graphical method, the unit peak discharge is read off a curve. However, the tabular method provides this information in the form of a table of values, found in Exhibit 5 of TR-55 (1986). These tables are arranged by rainfall type (I, IA, II, and III), I_a/P, T_c , and T_t . In most cases, the actual values for these variables, other than the rainfall type, will be different from the values shown in the table. Therefore, a system of rounding these values has been established in the TR-55 manual. The I_a/P term is simply rounded to the nearest table value. The T_c and T_t values are rounded together in a procedure that is outlined on pages 5-2 and 5-3 of TR-55 (1986). The accuracy of the computed peak discharge and time of peak discharge is highly dependent on the proper use of these procedures.

The following equation is then used to determine the flow at any time:

$$q = q_t \times A_{mi} \times Q$$

Tabular Hydrograph Peak Discharge Equation

q = hydrograph coordinate in cfs, at hydrograph time t
q_t = unit discharge at hydrograph time t from TR-55 Exhibit 5, csm/in
A_{mi} = drainage area of individual subarea, mi^2
Q = runoff, in.

The product of A_{mi} x Q is multiplied by each table value in the appropriate unit hydrograph in Exhibit 5 of TR-55 (1986) (each sub-watershed may use a different unit hydrograph) to generate the actual hydrograph for the sub-watershed. This hydrograph is tabulated on TR-55 Worksheet 5b and added together with the hydrographs from the other sub-watersheds, being careful to use the same time increment for each sub-watershed. The result is a composite hydrograph at the bottom of the worksheet for the entire watershed.

NOTE:

TR-55 documentation should be referenced for complete procedures and limitations of the Tabular Method.

Examples and worksheets can be found in TR-55 (1986). Revisions to TR-55 along with instructions and examples for the windows software application are available in the WinTR-55 User Guide. The technical reference for WinTR-55 is the NRCS National Engineering Handbook.

Notes

Module 10 Problems

1. If the soil is nearly impervious clay with a high water table and has a high runoff potential, what is the Hydrologic Soil Group?

   From TR-55, (reproduced in Figure 10-2 on page 10):

   Hydrologic Soil Group =

2. Given a residential district with 1/2 acre lots, what is the Runoff Curve Number for Hydrologic Soil Group C?

   From TR-55, Table 2-2a, (reproduced in Figure 10-3 on page 12):

   Runoff Curve Number, CN =

3. Given a site with soils consisting of deep well-drained sands with 3 acres of impervious area, 2 acres of grass in fair condition, and 4 acres of woods in fair condition, what is the weighted Curve Number?

   From TR-55: Hydrologic Soil Group (reproduced in Figure 10-2 on page 10) =

   From TR-55, Tables 2-2a and 2-2c, (reproduced in Figure 10-3 and Figure 10-4 on pages 12 and 13):

Land use:	CN	x	Area	=	CN x A
Impervious	( )	x	( )	=	( )
Grass	( )	x	( )	=	( )
Woods	( )	x	( )	=	( )
Total CN x A =					( )

   CN, Weighted Average Runoff Curve Number =

   Total CN x A / Total A (acres) =

4. If 3% of the watershed consists of ponds and swamps, what is the Pond and Swamp Adjustment Factor, F_p?

   Percentage of pond and swamp areas =

   From TR-55 Table 4-2, (reproduced in Figure 10-19 on page 29)

   Fp =