Module 3: Stormwater Engineering Concepts

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Objectives

- Recall basic stormwater engineering concepts for estimating runoff from small watersheds using TR-55, the Rational Method, and Modified Rational Method
- Explain estimation of detention volume required to attenuate peak flows
- Describe the basics for developing discharge rating curves for weirs and orifices used in the design of spillways

3a. Why Stormwater Engineering Concepts?

Roadmap to Water Quantity & Quality

Water Quantity	Water Quality	Natural Processes
• Channel/Flood Protection *(9VAC25-870-66)* • Discharge • Volume • Duration	• Runoff Reduction Method • (9VAC25-870-63) • Concentration • Volume • Load (mg/L * ft3)	• Land Cover Types/Soils • Minimize impacts • Mimic (ESD) • Using Runoff Reduction Method

Part II B of the VSMP Regulations (9VAC25-870-72) provides general technical criteria for acceptable design storms and hydrologic methods used to demonstrate compliance with the specific technical criteria of Part II B:

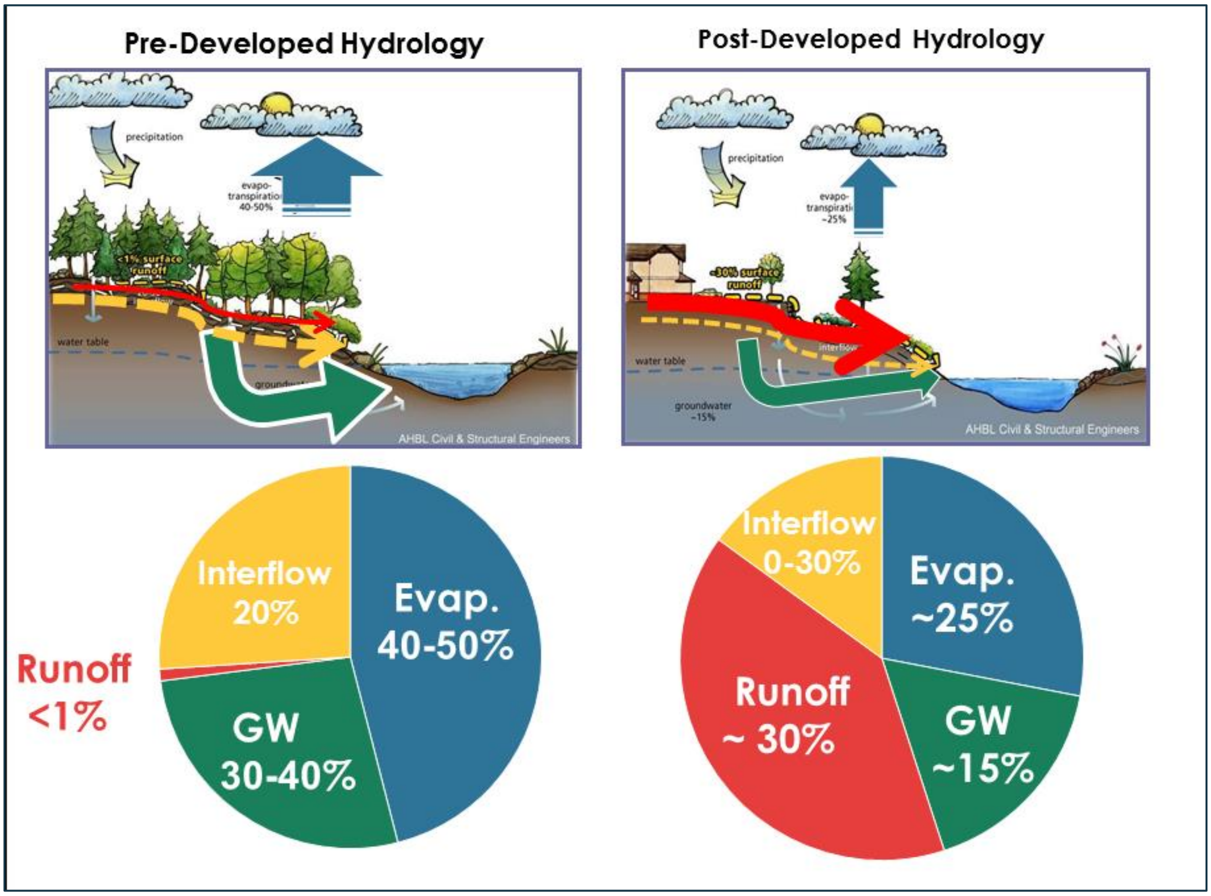
- Design storms are the **1-, 2-, and 10-year 24-hour storms**.
- Use the site-specific rainfall precipitation frequency data recommended by the U.S. **National Oceanic and Atmospheric Administration (NOAA) Atlas 14**.
- The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) synthetic **24-hour rainfall distribution** and models, including, but not limited to **TR-55** and TR-20; hydrologic and hydraulic methods developed by the U.S. Army Corps of Engineers; or other standard hydrologic and hydraulic methods, shall be used.
- For **drainage areas ≤ 200 acres**, the VSMP authority may allow for the use of the **Rational Method** for evaluating peak discharges and the **Modified Rational Method** for evaluating volumetric flows.

Part II C of the VSMP Regulations (9VAC25-870-95) also provide general technical criteria for acceptable stormwater engineering methods used to demonstrate compliance with the technical criteria as **applicable to LDAs with continued permit coverage or that are grandfathered** as defined in the Regulations. The general criteria are similar to the requirements for Part II B projects, with some exceptions:

- Determination of flooding and channel erosion impacts to receiving streams due to land-disturbing activities shall be measured at each point of discharge from the land disturbance and such determination **shall include any runoff from the balance of the watershed that also contributes to that point of discharge**.
- The specified design storms shall be either a **24-hour storm using the rainfall distribution** recommended by the NRCS when using NRCS methods, or the **storm of critical duration that produces the greatest required storage volume** at the site when using a design method such as the Modified Rational Method.
- Pervious lands in the site shall be assumed prior to development to be in **good condition** (if the lands are pastures, lawns, or parks), with **good cover** (if the lands are woods), or with **conservation treatment** (if the lands are cultivated); regardless of conditions existing at the time of computation.
- Predevelopment and postdevelopment runoff rates shall be verified by calculations that are consistent with **good engineering practices**.
- Subdivisions shall apply the stormwater management criteria to the land disturbance as a whole. Individual lots in new subdivisions shall not be considered separate land-disturbing activities, but rather the entire subdivision shall be considered a single land development project. **Hydrologic parameters shall reflect the ultimate land disturbance and shall be used in all engineering calculations**.

This module of the Participant Guide focuses on basic stormwater engineering practices and the use of the NRCS' <u>Technical Release 55 (TR-55): Urban Hydrology for Small Watersheds</u>. The Rational and Modified Rational Methods is introduced and briefly discussed, and a basic introduction is provided to hydraulic calculations for weirs and orifices used in spillways and other hydraulic control structures related to stormwater management engineering.

3b. Hydrologic Cycle



As population growth increases, the demand for buildings, homes and infrastructure also increases. In the past, development often led to the loss of many important environmental processes including:

- Reduced evapotranspiration, interception, and infiltration from the loss of vegetation;
- Reduced infiltration from the removal of topsoil and compaction of subsoil;
- Reduced groundwater recharge and stream base flows from increased stormwater runoff over impervious surfaces;
- Reduced infiltration from the use of built drainage systems such as gutters, storm sewers and smooth-lined channels; and
- Declining watershed health from increased imperviousness.

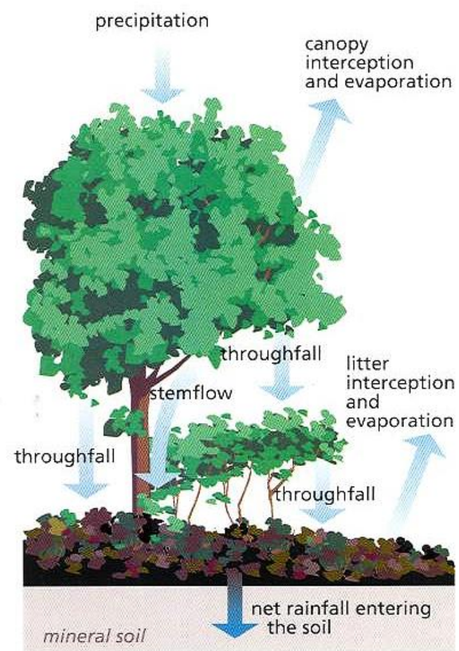
It's important to remember that altering one component of the water cycle affects all other elements of the cycle. Roads, buildings, parking lots and other impervious surfaces prevent rainfall from infiltrating into the soil and significantly increase runoff volume and flow.

As natural vegetation is replaced with impervious cover and natural drainage patterns are altered, the amount of evapotranspiration and infiltration decreases and stormwater runoff substantially increases.

Reduced evapotranspiration and infiltration from loss of vegetation

In a natural Virginia woodland or meadow, very little rainfall leaves the site as runoff. Runoff will occur from most wooded sites only after more than an inch of rain has fallen. In an undeveloped area, more than half of the annual amount of rainfall returns to the atmosphere through evapotranspiration.

Turf grass, which has commonly been used to replace natural vegetation, produces more runoff than natural open space and forestland, often because it is laid over compacted soil. Turf grass management can involve the application of large amounts of fertilizer and pesticides, which can be picked up by stormwater runoff and carried to local waterways.



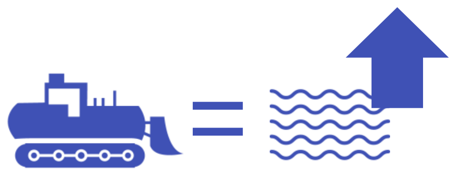
The benefits of tree canopy for stormwater management

NOTE:

Removing vegetation or changing the land type from woods and meadow to residential lawns reduces evapotranspiration and infiltration and increases stormwater runoff volume and flow.

Reduced infiltration from removal of topsoil and compaction of subsoil

When soil is disturbed by grading, stockpiling, and heavy equipment traffic, the soil becomes compacted, structure is lost, and the ability of water to flow in (infiltration) and through (percolation) the soil decreases. ***When this happens, the soil's ability to take in water (permeability) is substantially reduced and surface runoff increases***. Soil permeability is very important when selecting BMPs that rely on infiltration to remove pollutants or reduce runoff volumes.



Reduced groundwater recharge and reduced stream base flows

When precipitation runs off impervious surfaces rather than infiltrating and recharging the groundwater, it alters the hydrologic balance of the watershed. As a consequence, a stream's base flow is deprived of constant groundwater discharge, and the flow may diminish or even cease. Wetlands and headwaters reflect changes in groundwater levels most profoundly, and the reduced flow can stress or even eliminate the aquatic community.

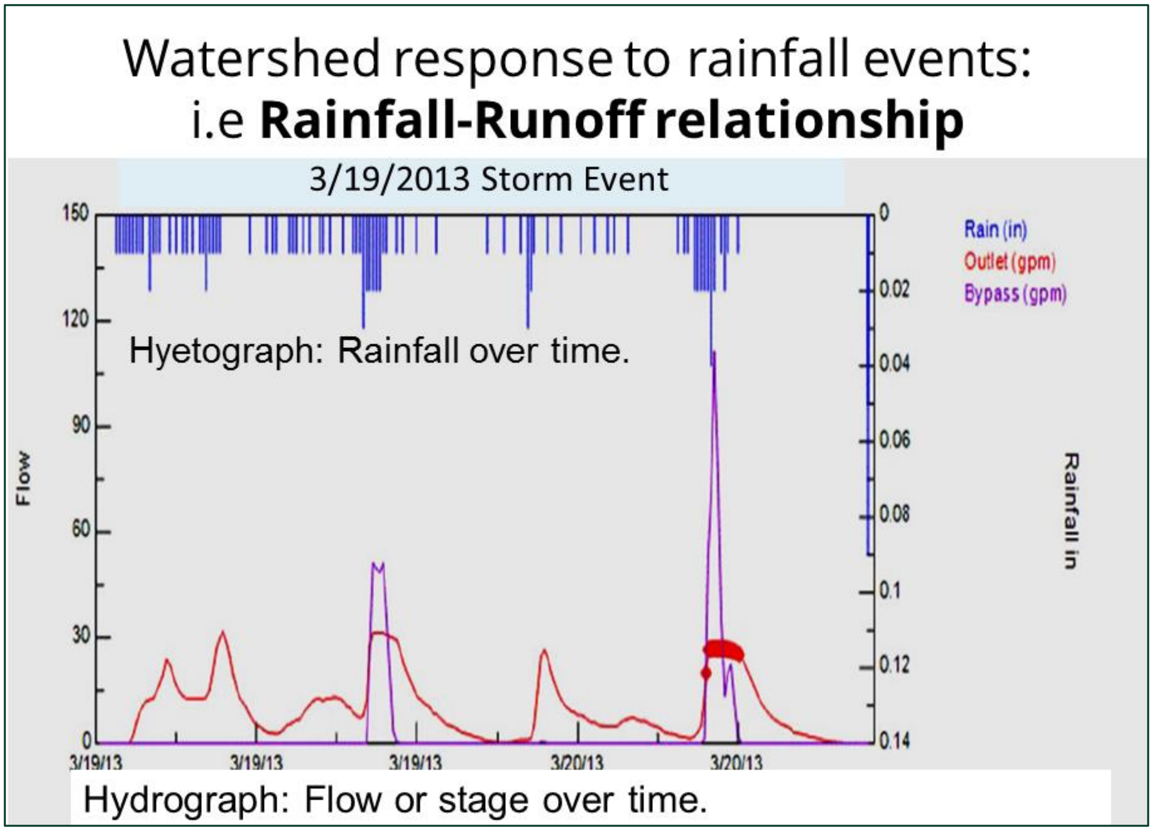
During a drought, reduced stream base flow may also significantly affect the water quality in a stream. As the amount of water in the stream decreases, the oxygen content of the water often falls, affecting the fish and macroinvertebrates that live there. Reduced oxygen content can also lead to the release of pollutants previously bound up in bottom sediment.

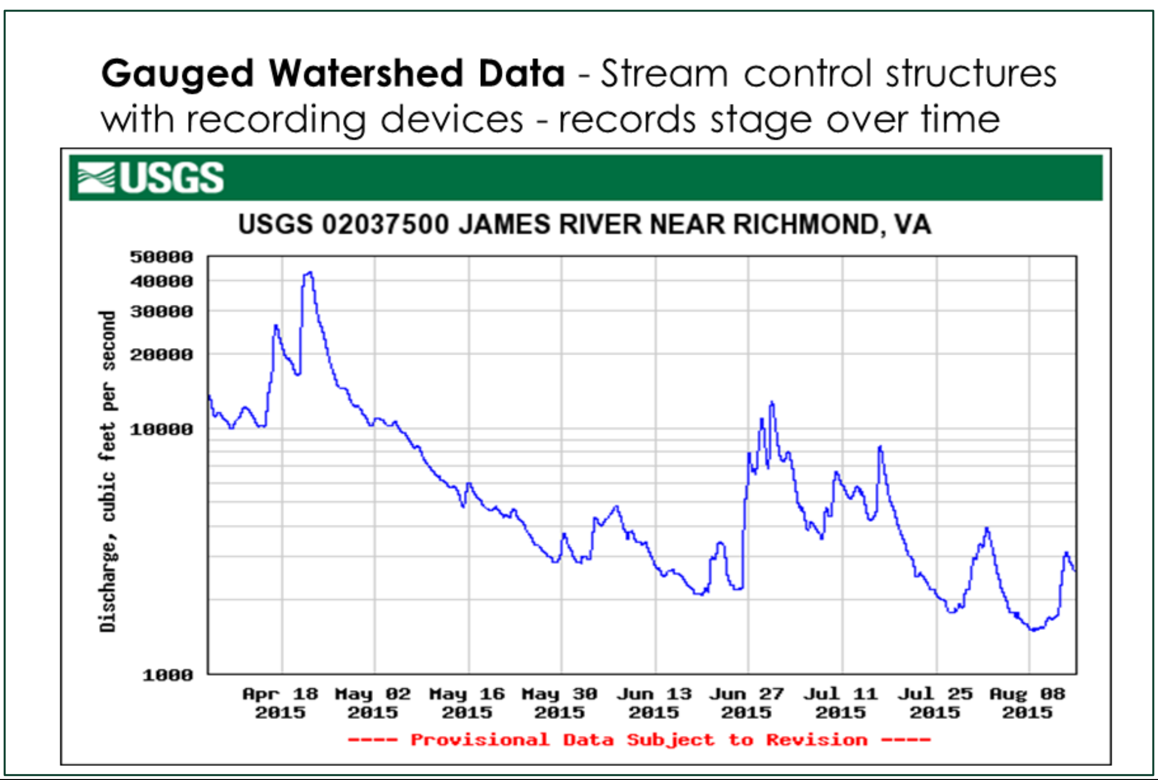
Reduced infiltration from built or traditional drainage systems

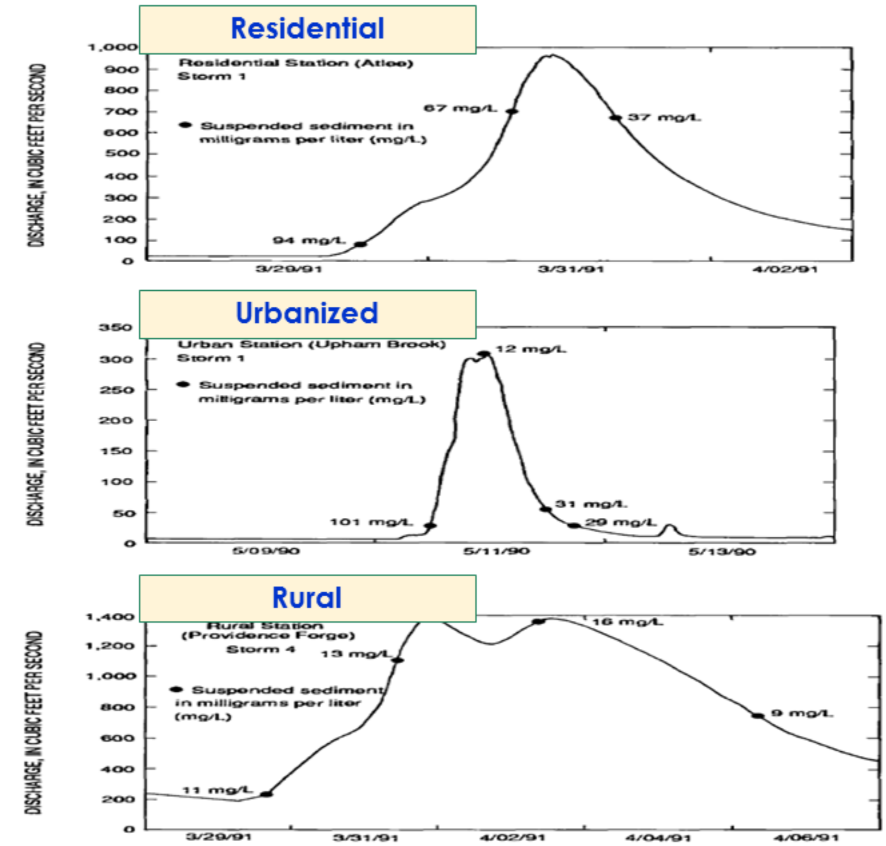
As stated earlier, depending on the magnitude of changes to the land surface, the total runoff volume can increase dramatically. This effect is further intensified by drainage systems such as gutters, storm sewers and smooth-lined channels that are designed to quickly carry runoff to rivers and streams.

3c. Water Quantity

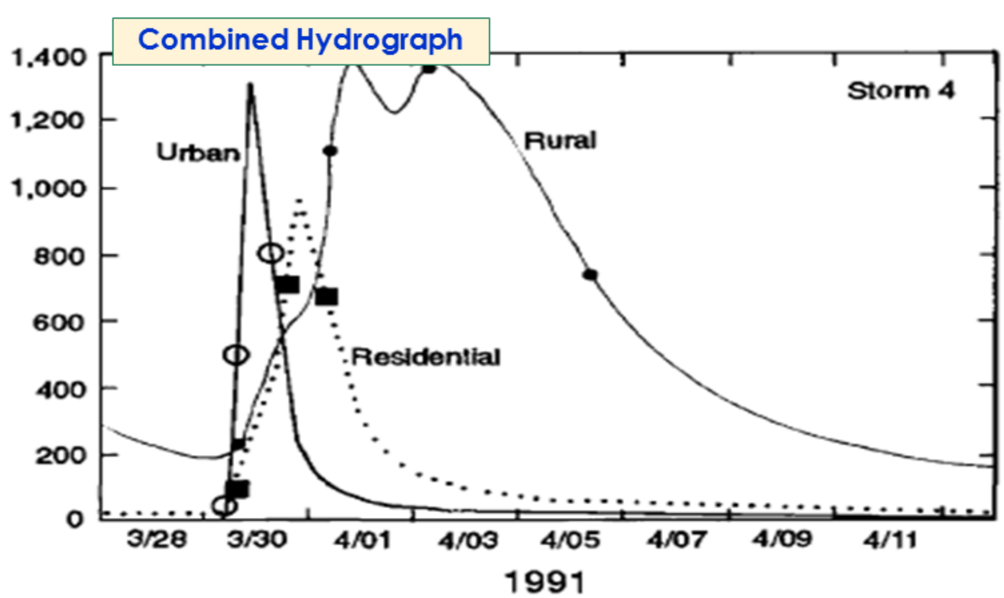
3c1. Rainfall-Runoff Relationships







Rainfall-Runoff Relationships



Rainfall-Runoff Relationships:

Impossible to collect at every discharge point of interest

Each method limited in specific runoff parameters it can provide

Rainfall-Runoff Coefficients

Methods used for various design applications

- Rational Method
- Modified Rational Method
- NRCS TR-55

Methods estimate runoff quantity from rainfall based on land cover types

- CN
- C-Value
- Runoff coefficient Rv

Rainfall-Runoff Coefficients

- Function of watershed response to rainfall event
- Includes watershed characteristics: slope, cover, soil type
- Individual project sites
  - Information never available
- Estimate with models
  - Runoff estimated from selected rainfall characteristics
  - Coefficients used to estimate runoff from rainfall intensities/amounts
- C value (Rational), Rv (Simple Method), CN (TR-55)
  - All take into account land cove types
  - Only CN and Rv account for soil types

3c2. Rational Method

The Rational Method was introduced in 1880 for determining peak discharges from drainage areas. It is frequently criticized for its simplistic approach, but this same simplicity has made the Rational Method one of the most widely used techniques today. The Rational Formula estimates the peak rate of runoff at any location in a drainage area as a function of the runoff coefficient (C), mean rainfall intensity (I), and drainage area (A).

The Rational Formula is expressed as follows:

$$Q = C \times I \times A$$

Rational Formula

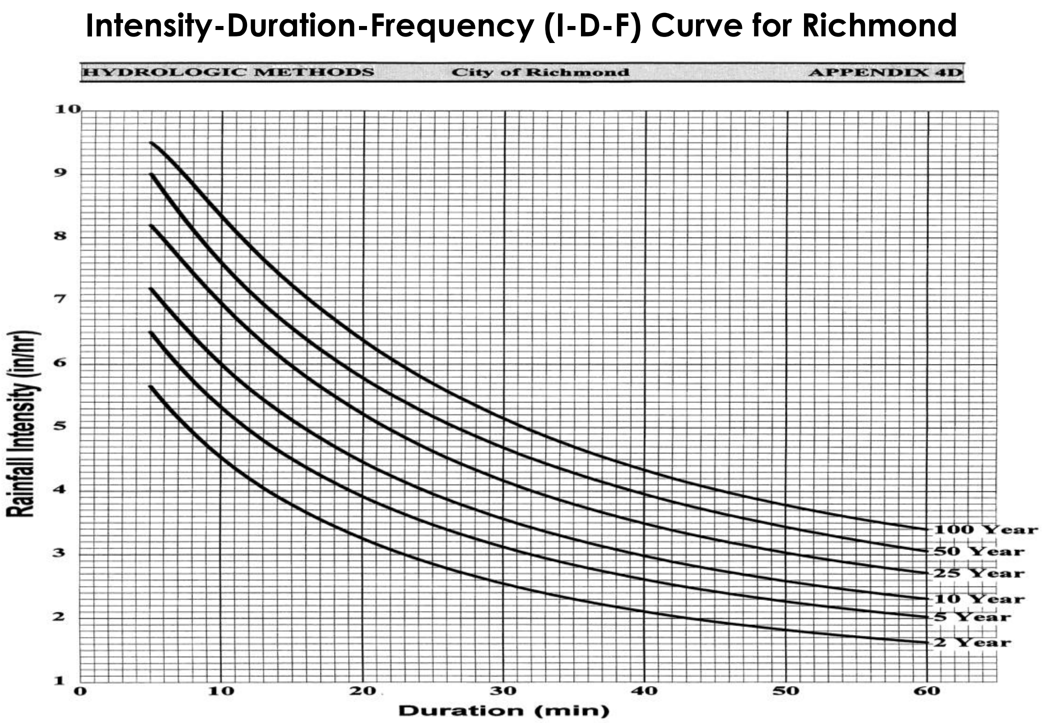
Q = maximum rate of runoff, cfs
C = dimensionless runoff coefficient, dependent upon land use
I = design rainfall intensity, in inches per hour, for a duration equal to the time of concentration of the watershed
A = drainage area, in acres

Table 3-1 Rational Formula Runoff Coefficients
(Source: VSWMH, 1999; page 4-20)

Land use	"C" Value
Business, industrial and commercial	0.90
Apartments	0.75
Schools	0.60
Residential - lots of 10,000 *sq. ft.*	0.50
- lots of 12,000 *sq. ft.*	0.45
- lots of 17,000 *sq. ft.*	0.45
- lots of ½ acre or more	0.40
Parks, cemeteries and unimproved areas	0.34
Paved and roof areas	0.90
Cultivated areas	0.60
Pasture	0.45
Forest	0.30
Steep grass slopes (2:1)	0.70
Shoulder and ditch areas	0.50
Lawns	0.20

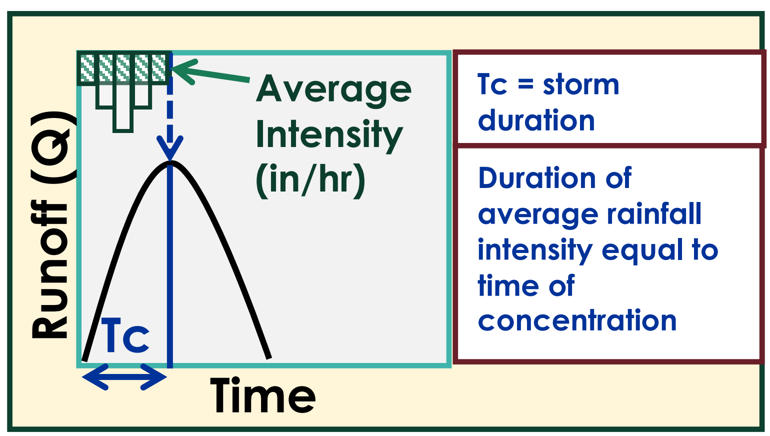
Table 3-2 Rational Formula Frequency Factors
(Source: VSWMH, 1999; page 4-20)

C_f	Storm Return Frequency
1.0	10 *yr.* or less
1.1	25 *yr.*
1.2	50 *yr.*
1.25	100 *yr.*



Rational Method Assumptions

The Rational Method is based on the following assumptions:



1. *Under steady rainfall intensity, the maximum discharge will occur at the watershed outlet at the time when the entire area above the outlet is contributing runoff.*

   This "time" is commonly known as the time of concentration, T_c, and is defined as the time required for runoff to travel from the most hydrologically distant point in the watershed to the outlet.

   The assumption of steady rainfall dictates that even during longer events, when factors such as increasing soil saturation are ignored, the maximum discharge occurs when the entire watershed is contributing to the peak flow, at time $t = T_c$.

   Furthermore, this assumption limits the size of the drainage area that can be analyzed using the rational method. In large watersheds, the time of concentration may be so long that constant rainfall intensities may not occur for long periods. Also, shorter, more intense bursts of rainfall that occur over portions of the watershed may produce large peak flows.

2. *The time of concentration is equal to the minimum duration of peak rainfall.*

   The time of concentration reflects the minimum time required for the entire watershed to contribute to the peak discharge as stated above. The rational method assumes that the discharge does not increase as a result of soil saturation, decreased conveyance time, etc.

   Therefore, the time of concentration is not necessarily intended to be a measure of the actual storm duration, but simply the critical time period used to determine the rainfall intensity from the Intensity-Duration-Frequency curves.

3. *The frequency or return period of the computed peak discharge is the same as the frequency or return period of rainfall intensity (design storm) for the given time of concentration.*

   Frequencies of peak discharges depend not only on the frequency of rainfall intensity, but also the response characteristics of the watershed. For small and mostly impervious areas, rainfall frequency is the dominant factor since response characteristics are relatively constant. However, for larger watersheds, the response characteristics will have a much greater impact on the frequency of the peak discharge due to drainage structures, restrictions within the watershed, and initial rainfall losses from interception and depression storage.

4. *The fraction of rainfall that becomes runoff is independent of rainfall intensity or volume.*

   This assumption is reasonable for impervious areas, such as streets, rooftops, and parking lots. For pervious areas, the fraction of rainfall that becomes runoff varies with rainfall intensity and the accumulated volume of rainfall. As the soil becomes saturated, the fraction of rainfall that becomes runoff will increase. This fraction is represented by the dimensionless runoff coefficient (C).

   Therefore, the accuracy of the rational method is dependent on the careful selection of a coefficient that is appropriate for the storm, soil, and land use conditions. Selection of appropriate C values will be discussed later in this chapter.

It is easy to see why the rational method becomes more accurate as the percentage of impervious cover in the drainage area approaches 100 percent.

5. *The peak rate of runoff is sufficient information for the design of stormwater detention and retention facilities.*

Rational Method Limitations

Because of the assumptions discussed above, the rational method should only be used when the drainage area is less than or equal to 200 acres. This is reflected in the VSMP Regulations at 9VAC25-870-72.

For larger watersheds, attenuation of peak flows through the drainage network begins to be a factor in determining peak discharge. While there are ways to adjust runoff coefficients (C factors) to account for the attenuation, or routing effects, it is better to use a hydrograph method or computer simulation for these more complex situations.

Similarly, the presence of bridges, culverts, or storm sewers may act as restrictions which ultimately impact the peak rate of discharge from the watershed. The peak discharge upstream of the restriction can be calculated using a simple calculation procedure, such as the Rational Method; however a detailed storage routing procedure which considers the storage volume above the restriction should be used to accurately determine the discharge downstream of the restriction.

Key Points

- **Peak flow in cubic feet per min. only**
- **Useful for design of culverts, inlets, etc.**
- **No volume determination**
- **No IDF or B,D,E constants for 1-year storm available**
- **Not well suited for VSMP compliance**

Rational Method Design Parameters

The following is a brief summary of the design parameters used in the rational method:

Time of concentration (T_c)

The most consistent source of error in the use of the rational method is the oversimplification of the time of concentration calculation procedure. Since the origin of the rational method is rooted in the design of culverts and conveyance systems, the main components of the time of concentration are inlet time (or overland flow) and pipe or channel flow time. The inlet or overland flow time is defined as the time required for runoff to flow overland from the furthest point in the drainage area over the surface to the inlet or culvert. The pipe or channel flow time is defined as the time required for the runoff to flow through the conveyance system to the design point. In addition, when an inlet time of less than 5 minutes is encountered, the time is rounded up to 5 minutes, which is then used to determine the rainfall intensity (I) for that inlet.

Variations in the time of concentration can impact the calculated peak discharge. When the procedure for calculating the time of concentration is oversimplified, as mentioned above, the accuracy of the Rational Method is greatly compromised. To prevent this oversimplification, it is recommended that a more rigorous procedure for determining the time of concentration be used, such as those outlined previously in this manual; Chapter 5 of the Virginia Erosion and Sediment Control Handbook, 1992 edition (VESCH, 1992); or Chapter 15, Section 4 of SCS National Engineering Handbook.

There are many procedures for estimating the time of concentration. Some were developed with a specific type or size watershed in mind, while others were based on studies of a specific watershed. The selection of any given procedure should include a comparison of the hydrologic and hydraulic characteristics used in the formation of the procedure, versus the characteristics of the watershed under study. The designer should be aware that if two or more methods of determining time of concentration are applied to a given watershed, there will likely be a wide range in results. The SCS method is recommended because it provides a means of estimating overland sheet flow time and shallow concentrated flow time as a function of readily available parameters such as land slope and land surface conditions. Regardless of which method is used, the result should be reasonable when compared to an average flow time over the total length of the watershed.

Rainfall Intensity (I)

The rainfall intensity (I) is the average rainfall rate, in inches per hour, for a storm duration equal to the time of concentration for a selected return period (i.e., 1-year, 2-year, 10-year, 25-year, etc.). Once a particular return period has been selected, and the time of concentration has been determined for the drainage area, the rainfall intensity can be read from the appropriate rainfall Intensity-Duration-Frequency (I-D-F) curve for the geographic area in which the drainage area is located. These charts were developed from data furnished by the National Weather Service for regions of Virginia.

Runoff Coefficient (C)

The runoff coefficients for different land uses within a watershed are used to generate a single, weighted coefficient that will represent the relationship between rainfall and runoff for that watershed. Recommended coefficients (based on urban land use only) can be found in Table 3-1 above.

A good understanding of these parameters is essential in choosing an appropriate coefficient. As the slope of a drainage basin increases, runoff velocities increase for both sheet flow and shallow concentrated flow. As the velocity of runoff increases, the ability of the surface soil to absorb the runoff decreases. This decrease in infiltration results in an increase in runoff. In this case, the designer should select a higher runoff coefficient to reflect the increase due to slope.

Soil properties influence the relationship between runoff and rainfall even further since soils have differing rates of infiltration. Historically, the Rational Method was used primarily for the design of storm sewers and culverts in urbanizing areas; soil characteristics were not considered, especially when the watershed was largely impervious. In such cases, a conservative design simply meant a larger pipe and less headwater. For stormwater management purposes, however, the existing condition (prior to development, usually with large amounts of pervious surfaces) often dictates the allowable post-development release rate, and therefore, must be accurately modeled.

Soil properties can change throughout the construction process due to compaction, cut, and fill operations. If these changes are not reflected in the runoff coefficient, the accuracy of the model will decrease. Some localities arbitrarily require an adjustment in the runoff coefficient for pervious surfaces due to the effects of construction on soil infiltration capacities. Such an adjustment is not possible using the Rational Method since soil conditions are not considered.

Adjustment for Infrequent Storms

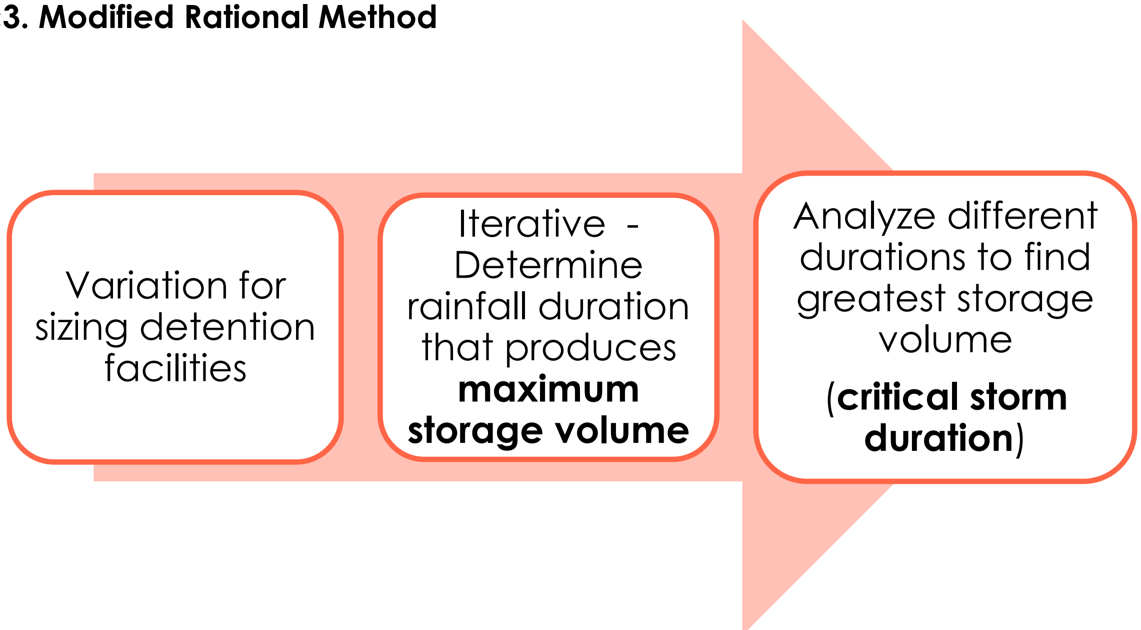
The Rational Method has undergone further adjustment to account for infrequent, higher intensity storms. This adjustment is in the form of a frequency factor (C_f) which accounts for the reduced impact of infiltration and other effects on the amount of runoff during larger storms.

With the adjustment, the Rational Formula is expressed as follows:

$$Q = C \times C_f \times I \times A$$

Where C_f values are provided in Table 3-2 above.

3c3. Modified Rational Method



The modified rational method is a variation of the rational method, developed mainly for the sizing of detention facilities in urban areas. The modified rational method is applied similarly to the rational method except that it utilizes fixed rainfall duration. The selected rainfall duration depends on the requirements of the user. For example, the designer might perform an iterative calculation to determine the rainfall duration which produces the maximum storage volume requirement when sizing a detention basin.

Modified Rational Method Assumptions

The modified rational method is based on the following assumptions:

1. *All of the assumptions used with the rational method apply. The most significant difference is that the time of concentration for the modified rational method is equal to the rainfall intensity averaging period rather than the actual storm duration.*

   This assumption means that any rainfall, or any runoff generated by the rainfall, that occurs before or after the rainfall averaging period is unaccounted for. Thus, when used as a basin sizing procedure, the modified rational method may seriously underestimate the required storage volume.

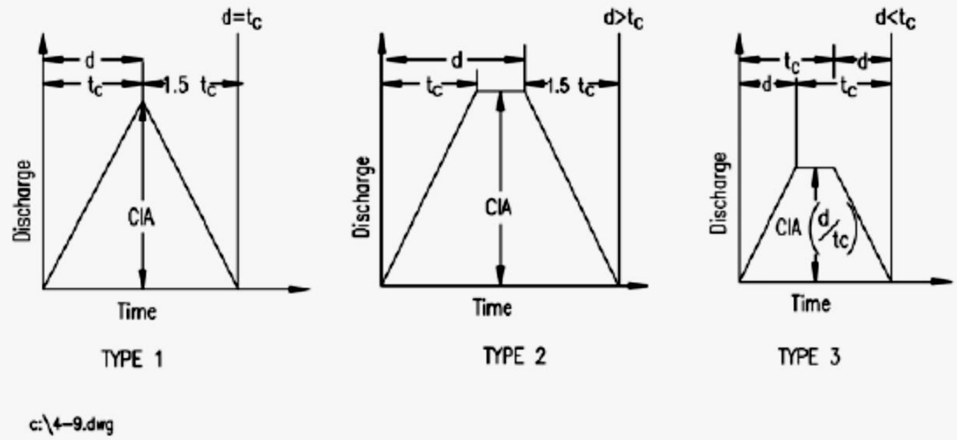
2. *The runoff hydrograph for a watershed can be approximated as triangular or trapezoidal in shape.*

   This assumption implies a linear relationship between peak discharge and time for any and all watersheds.

Modified Rational Method Limitations

All of the limitations listed for the rational method apply to the modified rational method. The key difference is the assumed shape of the resulting runoff hydrograph. The rational method produces a triangular shaped hydrograph, while the modified rational method can generate triangular or trapezoidal hydrographs for a given watershed, as shown in Figure 3-12.

Figure 3-1 Modified Rational Method Runoff Hydrographs
(Source: VSWMH, 1999**;** page 4-26)



Type 1 - Storm duration, d, is equal to the time of concentration, t_c.
Type 2 - Storm duration, d, is greater than the time of concentration, t_c.
Type 3 - Storm duration, d, is less than the time of concentration, t_c.

Modified Rational Method Design Parameters

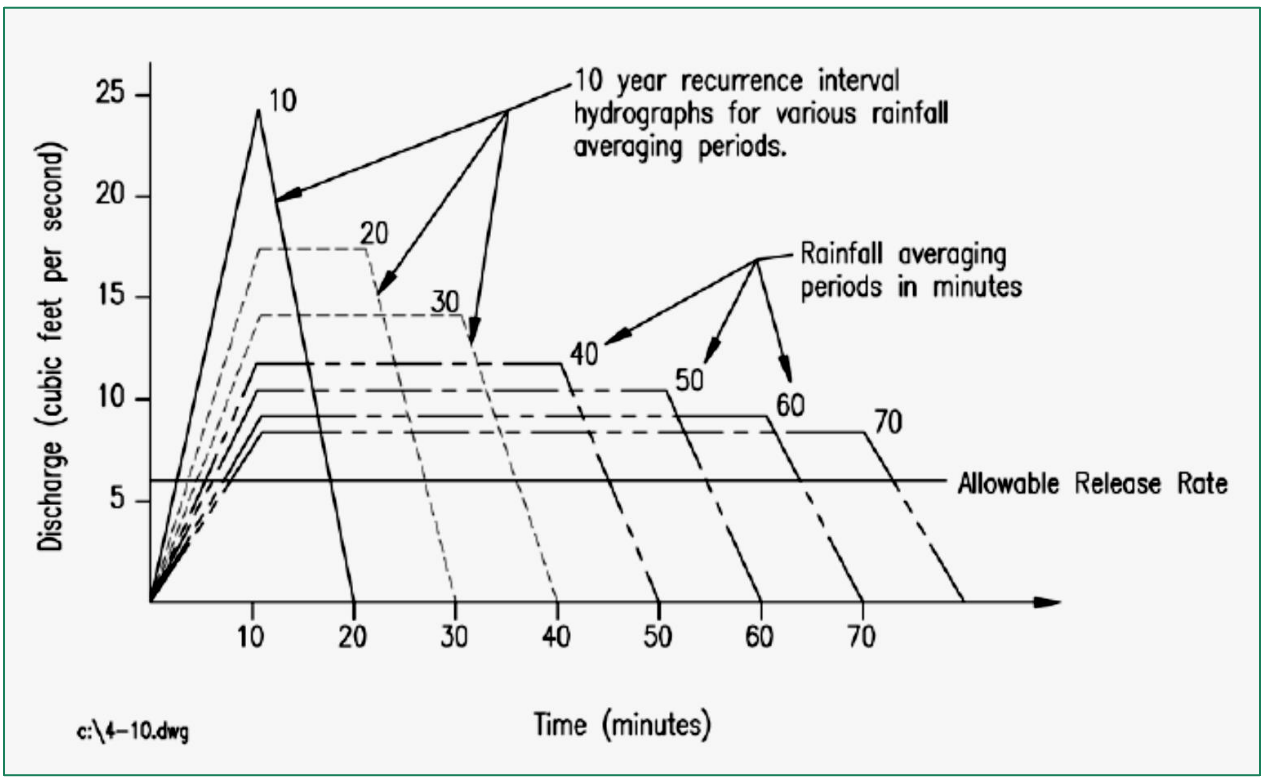
The equation Q = C x I x A (rational formula) is used to calculate the peak discharge for all three hydrographs shown in Figure 3-1. Notice that the only difference between the rational method and the modified rational method is the incorporation of the storm duration (d) into the modified rational method to generate a volume of runoff in addition to the peak discharge.

The rational method generates the peak discharge that occurs when the entire watershed is contributing to the peak (at a time t = T_c) and ignores the effects of a storm which lasts longer than time t. The modified rational method, however, considers storms with a longer duration than the watershed T_c , which may have a smaller or larger peak rate of discharge, but will produce a greater volume of runoff (area under the hydrograph) associated with the longer duration of rainfall. Figure 3-2 shows a family of hydrographs representing storms of different durations. The storm duration which generates the greatest volume of runoff may not necessarily produce the greatest peak rate of discharge.

Note that the duration of the receding limb of the hydrograph is set to equal the time of concentration (T_c), or 1.5 times T_c. The direct solution, which is discussed in Chapter 5 of the VSWMH (1999 edition), uses 1.5 times T_c as the receding limb. This is justified since it is more representative of actual storm and runoff dynamics. (It is also more similar to the NRCS unit hydrograph where the receding limb extends longer than the rising limb.) Using 1.5 times T_c in the direct solution methodology provides for a more conservative design and will be used in this guide.

The modified rational method allows the designer to analyze several different storm durations to determine the one that requires the **greatest storage volume** with respect to the allowable release rate. This storm duration is referred to as the **critical storm duration** and is used as a basin sizing tool.

Figure 3-2 Modified Rational Method Runoff Hydrographs
(Source: VSWMH, 1999; page 4-27)



3c4. Urban Hydrology for Small Watersheds (TR-55)

Introduction (Chapter 1 of 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 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 the NRCS in TR-55 are based on a dimensionless rainfall distribution curve for a 24-hour storm.

When the second edition of TR-55 was published, the Natural Resources Conservation Service (NRCS) was known as the Soil Conservation Service (SCS). When you see SCS referenced in TR-55 and other document published prior to the name change, you may still see SCS referenced instead of the current NRCS. This document cites the NRCS instead of the 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. For large areas it may be necessary to divide the area into sub-watersheds 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, the designer must determine the volume of runoff resulting from a given depth of precipitation and the time of concentration, T_c , for the watershed being analyzed. The methods for determining these values will be discussed briefly in this section.

Peak Discharge

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_c*'s 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.*

The reader is encouraged to review the TR-55 Manual 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 postdeveloped peak discharge control. This short-cut method is found in Chapter 6 of TR-55 and is discussed later in this Participants Guide. However, it should be noted that a more sophisticated computer model such as TR-20, HEC-HMS, or even TR-55 Tabular Hydrograph Method, should be used for analyzing complex, urbanizing watersheds.

Graphical Peak Discharge Information Needed

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 Method. For a detailed explanation of the terms listed, refer to Chapter 3 of TR-55.

- Drainage area, in square miles (mi^2)
- Time of Concentration, T_c , in hours (hr)
- Weighted runoff curve number, CN
- 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 I, IA, II, or III)

Graphical Peak Discharge Design Procedure

The TR-55 Peak Discharge Equation is:

$$q_p = q_u \times A_m \times Q \times F_p$$ (Source: TR-55, Eq. 4-1)

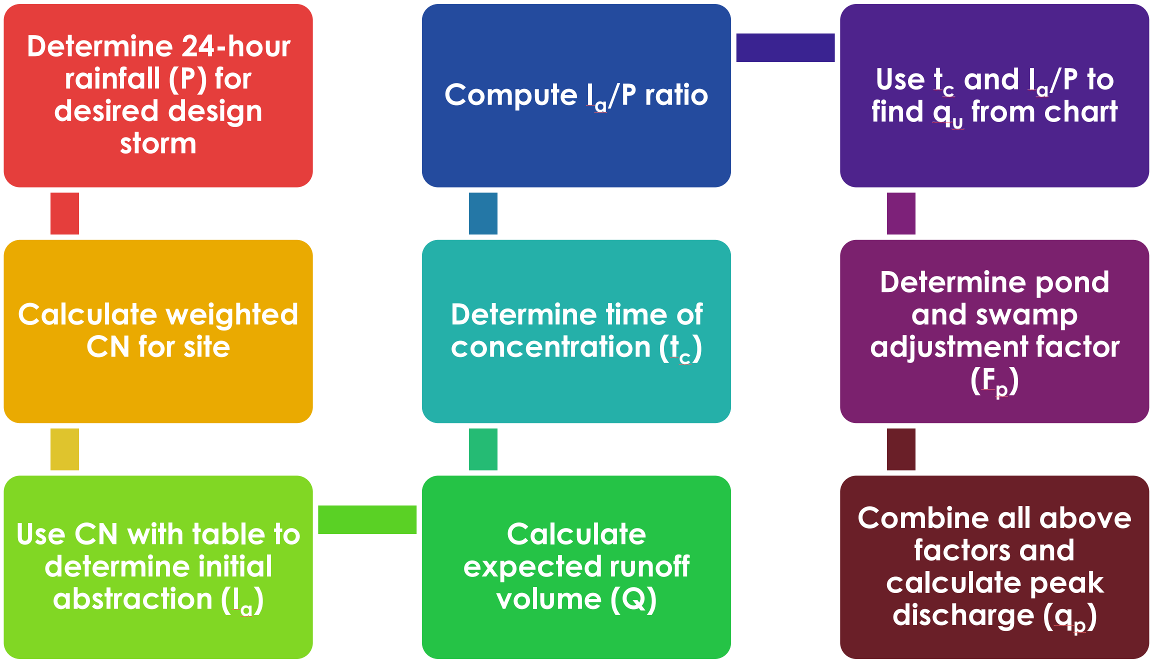
Peak Discharge Equation

Where:

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

The steps required to determine all the required information is shown in the following sections of this Module.

TR-55 Graphical Peak Discharge Method



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

Precipitation

- NOAA Atlas 14
- Distribution

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)

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

Synthetic Rainfall Distributions and Rainfall Data Sources (Appendix B of TR-55)

A common practice in rainfall-runoff analysis is to develop synthetic rainfall distributions to use in lieu of actual storm events, as the actual rainfall distribution will vary by event. The synthetic rainfall distribution includes maximum rainfall intensities for the selected design frequency arranged in a sequence that is critical for producing peak runoff. Appendix B of TR-55 presents a series of synthetic rainfall distributions developed by the NRCS, as discussed briefly below and in detail in TR-55.

Synthetic Rainfall Distributions

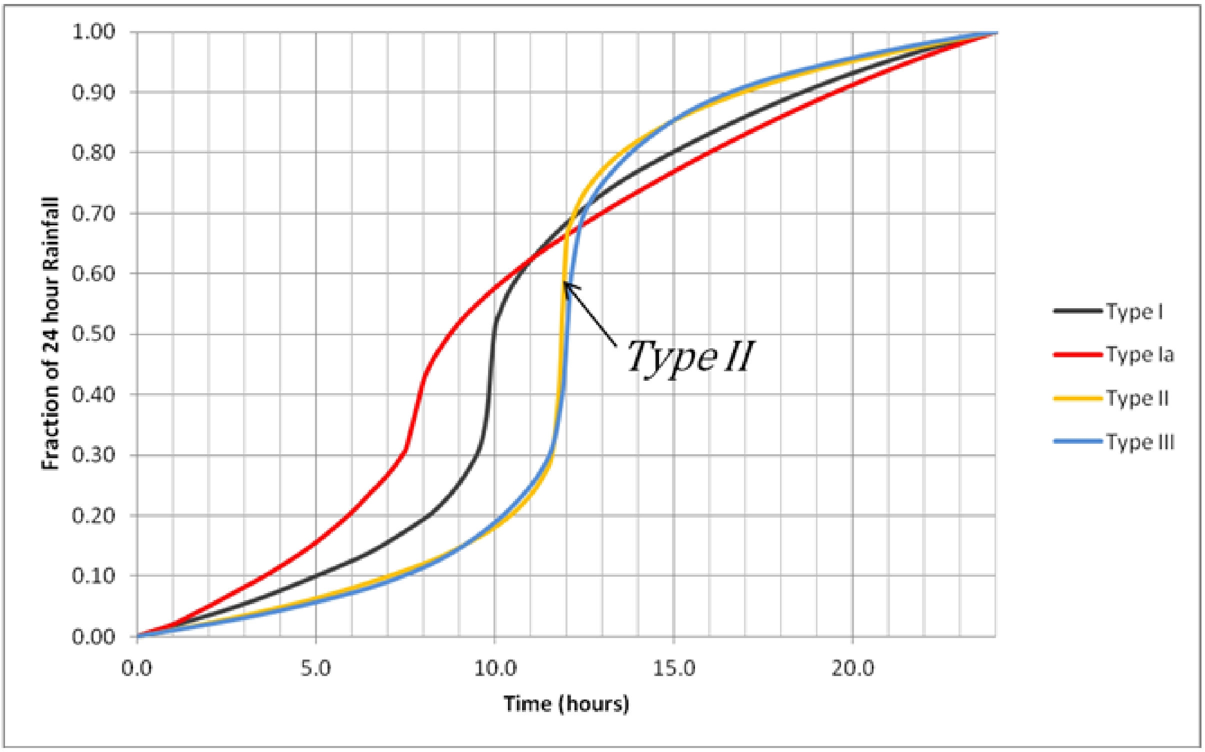
For the size of the drainage areas commonly evaluated for urban drainage and stormwater management, a storm period of 24 hours was chosen for the synthetic rainfall distributions prepared by the NRCS. The 24-hour storm, while longer than that needed to determine peak discharge, is appropriate for determining storm event runoff volumes. A single storm duration and associated synthetic rainfall distribution can be used to represent the peak discharges and the runoff volume.

The intensity of rainfall varies considerably during a storm as well as by geographic region. To represent various regions of the United States, NRCS developed four synthetic 24-hour rainfall distributions (I, IA, II, and III). Type IA is the least intense and type II the most intense short duration rainfall. Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type III represents Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts. Type II represents the rest of the country.

Figure 3-4 below is reproduced from TR-55 and shows the appropriate type of rainfall distribution based upon geographic boundaries across the United States. Figure 3-5 includes a view of the boundaries specific to Virginia.

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

Figure 3-3 Precipitation-Distribution (Source: TR-55)



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

Figure 3-4 Approximate Geographic Boundaries for U.S. (Source: TR-55)

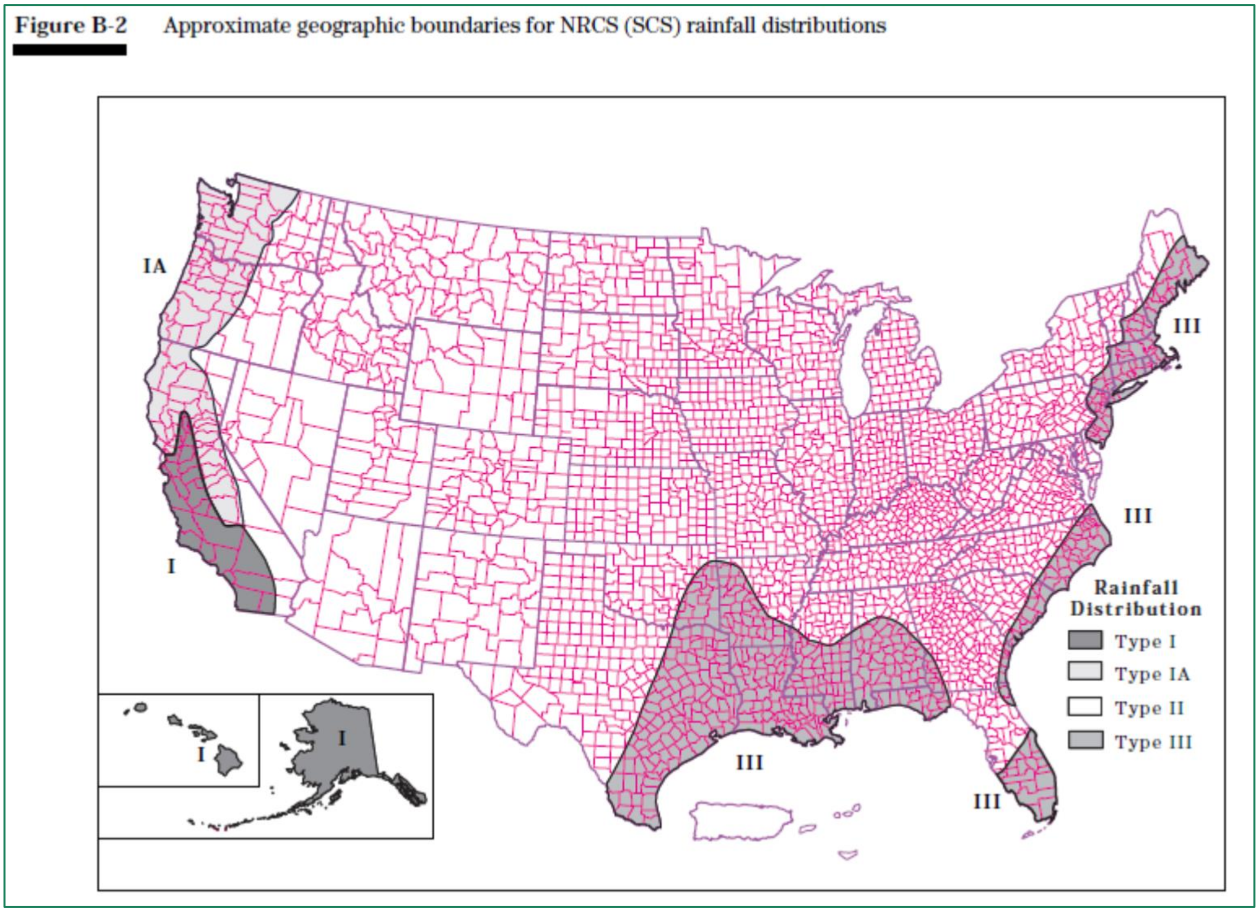
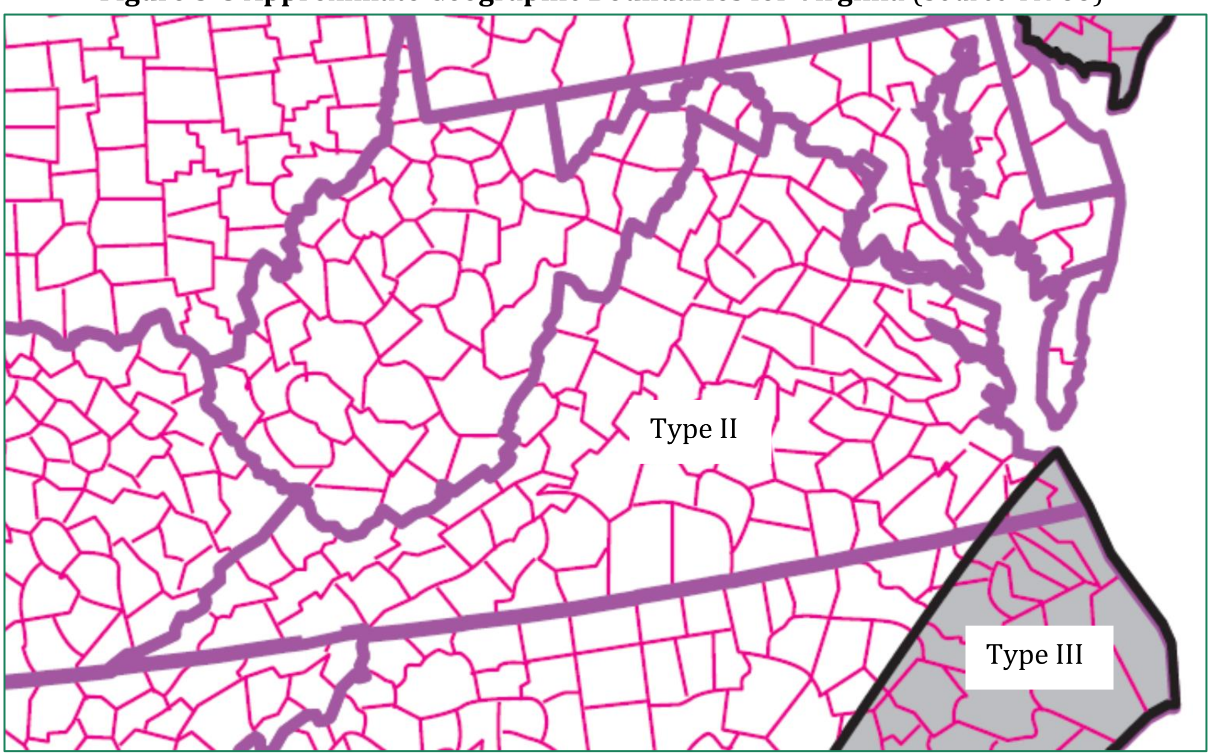


Figure 3-5 Approximate Geographic Boundaries for Virginia (Source TR-55)



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

Rainfall Data Sources

Rainfall depths for 24-hour distributions and different return periods/frequencies for the United States are provided in graphical format in TR-55, Appendix B, Figures B-3 to B-8 for the 2-, 5-, 10-, 25-, 50-, and 100-year storm events. A tabular presentation of 24-hour rainfall totals organized by Virginia City/County is included in Chapter 4 of the Virginia Stormwater Management Handbook, 1999 Edition (VSWMH, 1999), and includes the 1-year storm as well as the storm events reported in TR-55. These rainfall depths are based upon values published by the National Weather Service (NWS) in Technical Paper 40 (TP-40).

TP-40 was based upon historic rainfall data collected through the 1970s. A substantial amount of rainfall data has been collected since TP-40 was published, so the National Ocean and Atmospheric Administration (NOAA) published a new document that supersedes TP-40, titled Atlas 14 Precipitation-Frequency Atlas of the Eastern United States. The VSMP Regulations require that designers use updated rainfall data based upon the Atlas 14 publication for stormwater management computations and modeling.

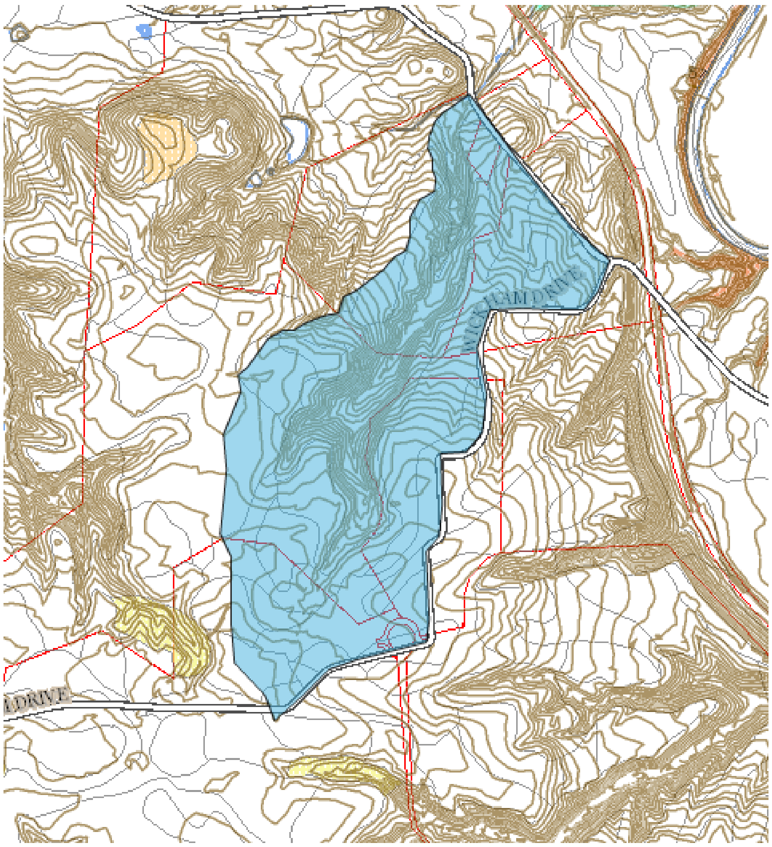
In January of 2008, the NRCS Virginia office published revised 24-hour rainfall depths for Virginia Cities and Counties based upon the NOAA Atlas 14 publication. The "Virginia Rainfall Data Using NOAA Atlas 14" is included in a State Supplement to the Engineering Field Handbook, Chapter 2 Estimating Runoff and Peak Discharges (210-VI-EFH, Part 650, pages 2-16c to 2-16e). The supplement includes updated tabulation of 24-hour rainfall totals the 1-, 2-, 5-, 10-, 25-, 50-, and 100-year events.

During the analysis of Virginia rainfall totals based upon Atlas 14, the NRCS determined that some localities have significantly different rainfall depths based upon geographic location within the City or County. As a result, some Cities or Counties may have multiple rainfall data sets reported based upon a geographic location within the locality. The NRCS publication noted above includes maps showing the breakdown of rainfall within localities with significantly different rainfall totals reported.

Calculate weighted CN for site

CN indicates:

- Runoff potential of an area



Watershed Delineation:

- Choose watershed outlet point
- Delineate watershed boundary (perpendicular lines across contour lines draining to point of interest

Note - A watershed boundary always runs perpendicular to contour lines

Calculate weighted CN for site

CN determination:

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

Calculate weighted CN for site

The NRCS Runoff Curve Number (CN) Method is used to estimate runoff. This method is described in detail in the NRCS National Engineering Handbook, Section 4 (NRCS 1985). 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.

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.

> The NRCS TR-55 manual should be reviewed in detail to gain more insight into the procedures and limitations.
>
> A digital copy of the TR-55 manual from the NRCS is available at: **ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/other/TR55documentation.pdf**

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, Ia 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. The designer should understand the assumptions reflected in the initial abstraction term (I_a). 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. (To use a relationship other than the one established in TR-55, the designer must redevelop the runoff equation by using the original rainfall-runoff data to establish new curve number relationships for each cover and hydrologic soil group. This would represent a large data collection and analysis effort.)

Calculate weighted CN for site

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 check, use another procedure to determine runoff.
5. The NRCS runoff procedures apply only to surface runoff and do not consider subsurface flow or high groundwater.
6. Manning's kinematic solution should not be used to calculate the time of concentration for sheet flow longer than 300 feet. This limitation will affect the time of concentration calculations. Note that many jurisdictions consider 150 feet to be the maximum length of sheet flow before shallow concentrated flow develops.
7. The minimum T_c used in TR-55 is 5 minutes or 0.1 hour.

Calculate weighted CN for site

Estimating Runoff (Chapter 2 of TR-55)

Information Needed

A good understanding of the physical characteristics of the watershed is needed to solve the runoff equation and determine the time of concentration. Some features, such as topography and channel geometry can be obtained from topographic maps such as the USGS 1" = 2000' quadrangle maps. Various sources of information may be accurate enough for a watershed study; however, the accuracy of the study will be directly related to the accuracy and level of detail of the base information. Ideally, a site investigation and field survey should be conducted to verify specific features such as channel geometry and material, culvert sizes, drainage divides, ground cover, etc. Depending on the size and scope of the study, however, a site investigation may not be economically feasible.

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.

- 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.)
- Topography – detailed enough to accurately identify drainage divides, T_c and T_t flow paths and channel geometry, and surface condition (roughness coefficient).

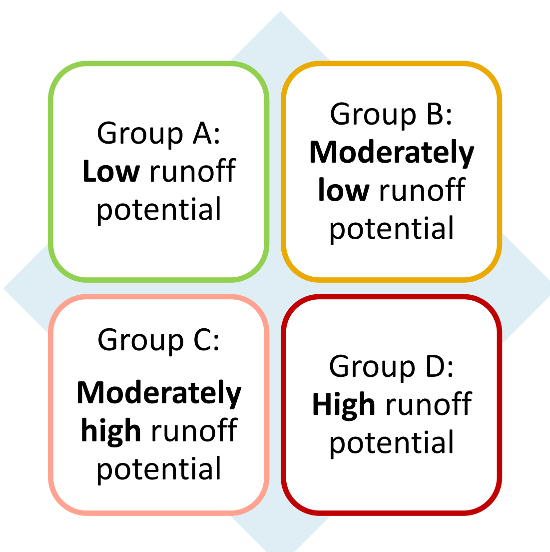
Calculate weighted CN for site

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.

NRCS has developed a soil classification system that consists of four **hydrologic soil groups (HSG)**, identified as A, B, C, and D. Soils are classified into one of these categories based upon their minimum infiltration rate. 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 especially useful for watershed analysis and planning in general. When preparing a stormwater management plan for a specific site, it is recommended that soil borings be taken to verify the hydrologic soil classification.

Soil characteristics associated with each HSG are generally described as follows:



Group A: Soils with low runoff potential due to high infiltration rates, even when thoroughly wetted. These soils consist primarily of deep, well to excessively drained sands and gravels with high water transmission rates (0.30 inches per hour or in/hr). Group A soils include sand, loamy sand, or sandy loam.

Group B: Soils with moderately low runoff potential due to moderate infiltration rates when thoroughly wetted. These soils consist primarily of moderately deep to deep, and moderately well to well-drained soils. Group B soils have moderate water transmission rates (0.15-0.30 in/hr) and include silt loam or loam.

Group C: Soils with moderately high runoff potential due to slow infiltration rates when thoroughly wetted. These soils typically have a layer near the surface that impedes the downward movement of water or soils. Group C soils have low water transmission rates (0.05-0.15 in/hr) and include sandy clay loam.

Group D: Soils with high runoff potential due to very slow infiltration rates. These soils consist primarily of clays with high swelling potential, soils with permanently high water tables, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious parent material. Group D soils have very low water transmission rates (0-0.05 in/hr) and include clay loam, silty clay loam, sandy clay, silty clay, or clay.

Any disturbance of a soil profile can significantly alter the soil's infiltration characteristics. With urbanization, the hydrologic soil group for a given area can change due to soil mixing, introduction of fill material from other areas, removal of material during mass grading operations, or compaction from construction equipment. A layer of topsoil may typically be saved and replaced after the earthwork is completed, but the native underlying soils have been dramatically altered. Therefore, any disturbed soil should be classified by its physical characteristics as given above for each soil group. 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 Table 3-3 below).

Table 3-3 HSG Based Upon Soil Texture for Disturbed Soils (Source: TR-55)

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

Hydrologic Condition

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

Calculate weighted CN for site

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 stormwater management regulations 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 which, 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. Tables 3-4 and 3-5 below (Tables 2-2a and 2-2c from TR-55) provide the CNs for various land use types and soil groups. A complete table can be found in TR-55.

Several factors should be considered when choosing a CN for a given land use. First, the designer should realize that the curve numbers in TR-55 are for 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.

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**

Calculate weighted CN for site

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 TR-55, Tables 2-2a to 2-2d. TR-55 provides a graphical solution for modification of the given CNs if any of these assumptions do not hold true.
6. The designer should become familiar with the definition of connected versus unconnected impervious areas along with the graphical solutions and the impact that their use can have on the resulting CN. After some experience in using this section of TR-55, the designer will be able to make field evaluations of the various criteria used in the determination of the CN for a given site.
7. In addition, the designer will need to determine if the watershed contains sufficient diversity in land use to justify dividing the watershed into several **sub-watersheds**. If a watershed or drainage area cannot be adequately described by one **weighted curve number**, then the designer must divide the watershed into sub-areas and analyze each one individually, generate individual hydrographs, and add those hydrographs together to determine the composite peak discharge for the entire watershed.
8. Figure 3-6 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 from which to then choose the runoff curve numbers. Worksheet 2 of TR-55 (see Figure 3-7) is then used to compute the weighted curve number for the area or sub-area.

Calculate weighted CN for site

Table 3-4 Runoff Curve Numbers for Urban Areas (Source: TR-55)

Table 2-2a Runoff curve numbers for urban areas [1]

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).					

Cover description; Curve numbers for hydrologic soil group (A, B, C, D).

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.

Calculate weighted CN for site

Table 3-5 Runoff Curve Numbers for Other Agricultural Lands (Source: TR-55)

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

Column groups: Cover description (Cover type, Hydrologic condition); Curve numbers for hydrologic soil group (A, B, C, 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.

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.

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

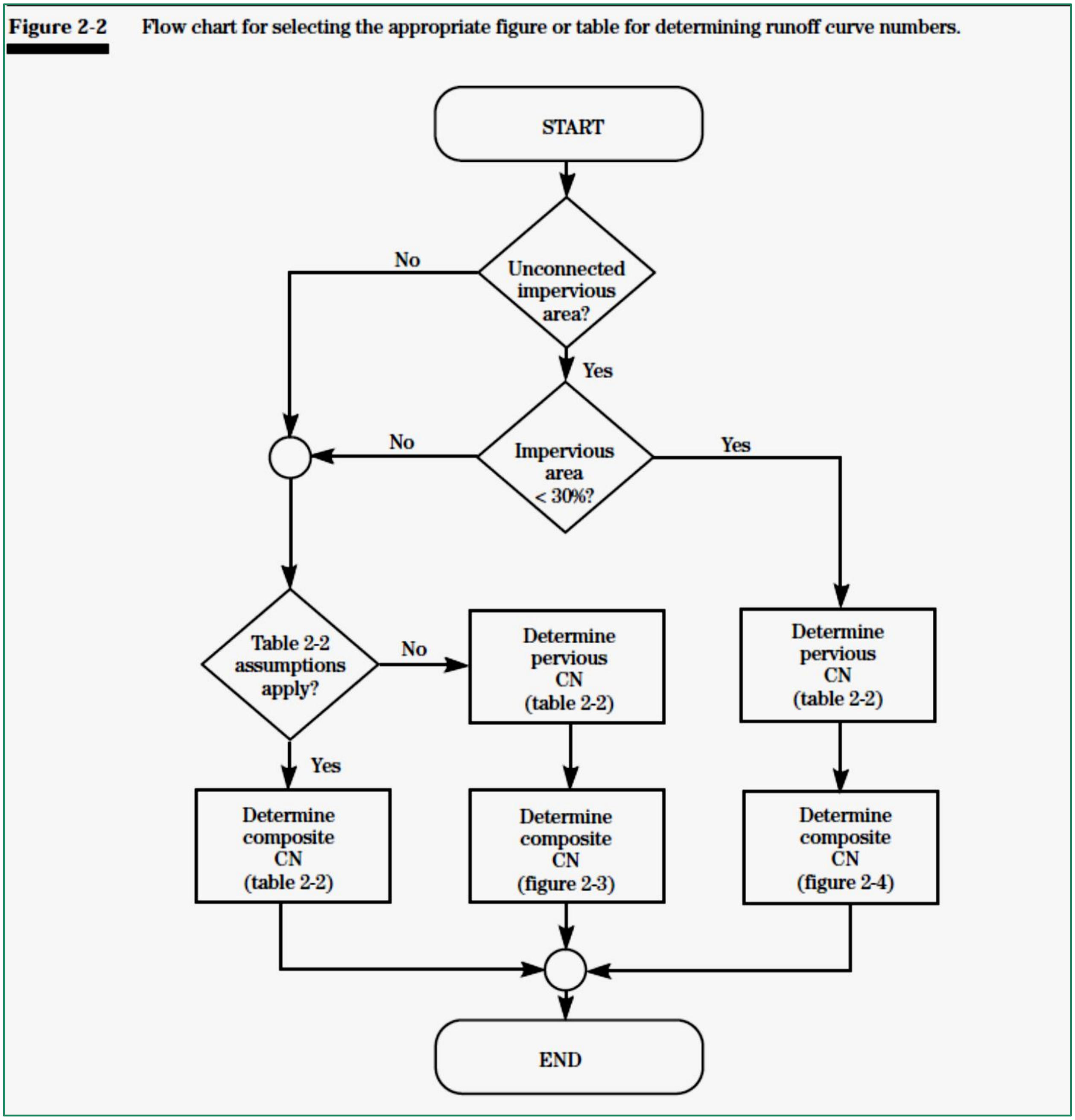
The CN values were developed assuming pervious urban areas are comparable to pasture in good condition, while impervious areas are directly connected to the drainage system with a CN of 98. Assumed percentages of impervious area are provided in Table 2-2a of TR-55 as reproduced in Table 3-4 above. If 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 can use Figure 2-3 of TR-55 (see Figure 3-8 below) to compute a composite CN.

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 can use Figure 2-4 of TR-55 (reproduced below as Figure 3-9) to determine the CN, provided the total impervious area is less than 30 percent. If the total impervious area is ≥ 30%, use Figure 3-8 (Figure 2-3 from TR-55) 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 **Environmental Site Design** and can provide **Runoff Reduction**, as discussed in Module 4 of this Participants Guide.

Calculate weighted CN for site

Figure 3-6 Flow Chart for Determining Runoff Curve Number (CN) (Source TR-55)



Calculate weighted CN for site

Figure 3-7 Worksheet 2 Runoff Curve Number and Runoff (Source TR-55)

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

[1/] Use only one CN source per line

Totals ➡

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	in			

(Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)

Calculate weighted CN for site

Figure 3-8 Composite CN with Connected Impervious Area or Impervious Area ≥ 30% of Drainage Area (Source TR-55)

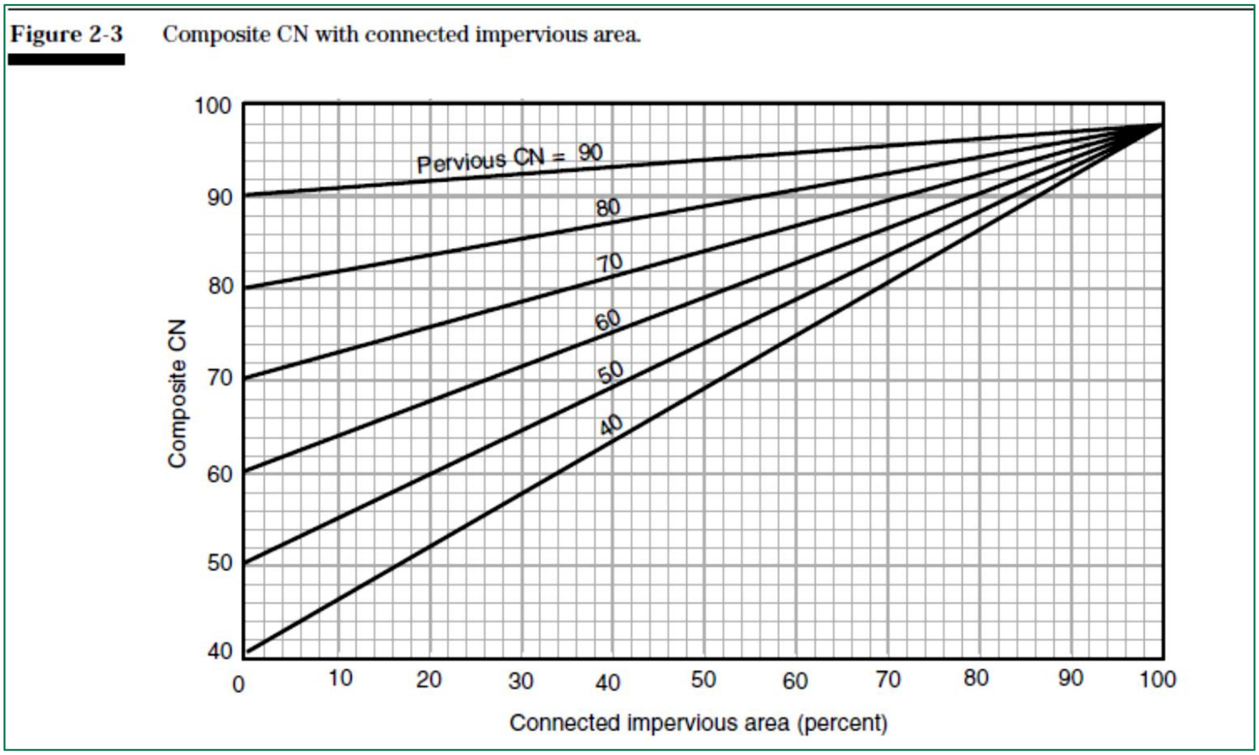
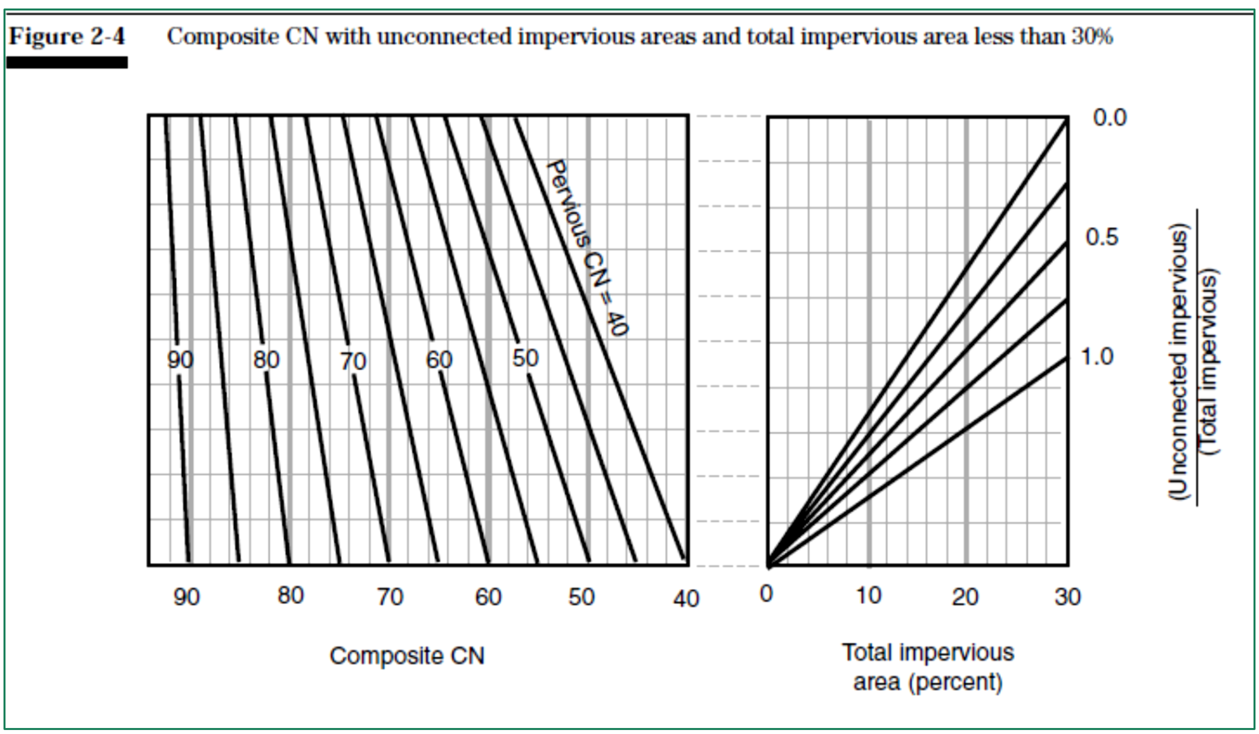


Figure 3-9 Composite CN with Unconnected Impervious Area and Total Impervious Area < 30% (Source TR-55)



Use CN with table to determine initial abstraction I_a

Table 3-6 I_a Values for Runoff Curve Numbers (Source: TR-55)

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		

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)

Where:

CN = Runoff Curve Number

Initial abstraction (Ia) 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 Table 4-1 in TR-55 or Table 3-6 above.

Runoff Equation

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 of which 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

Where:

Q = runoff, inches (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in) (Source: TR-55, Eq. 2-4)

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

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:

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

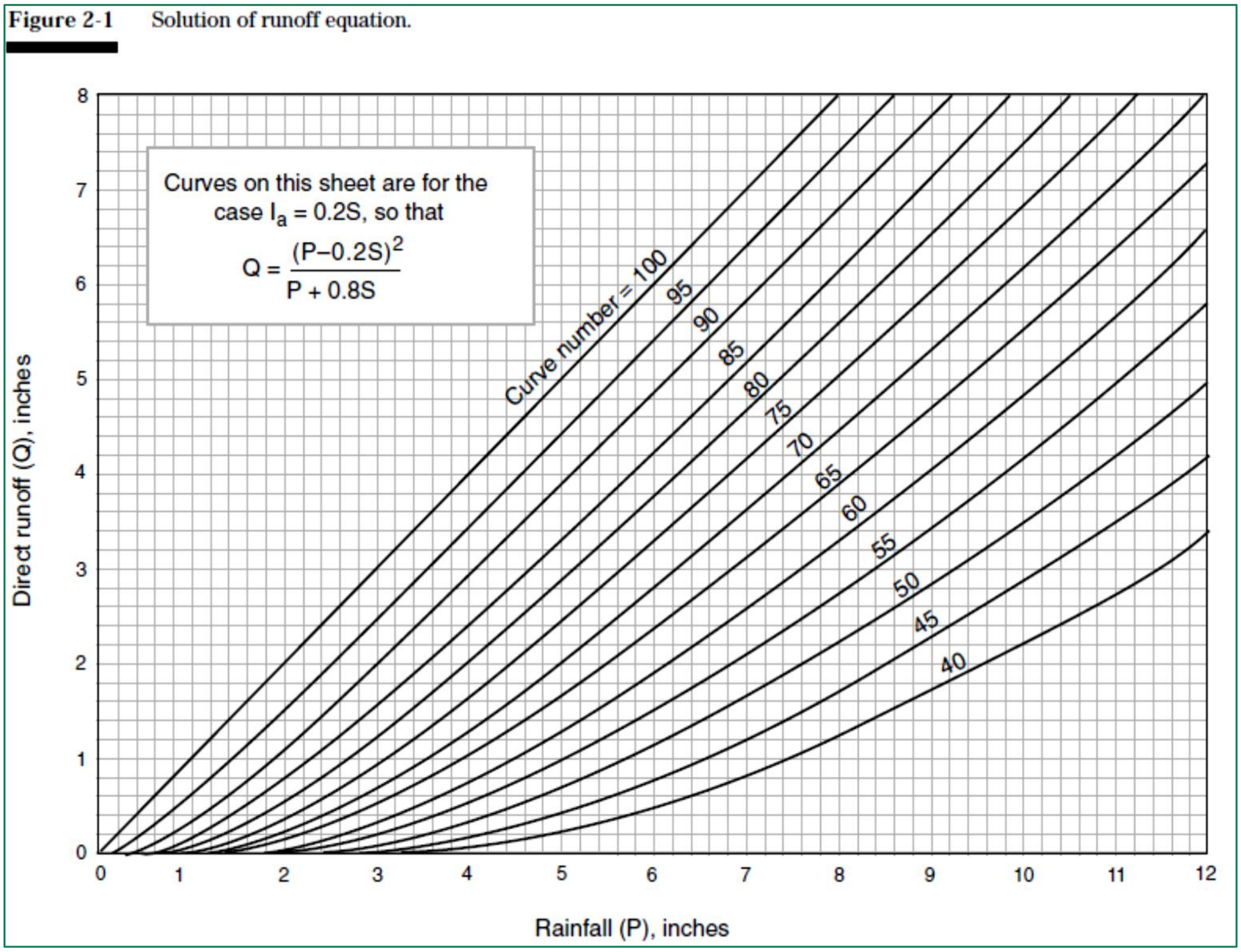
(Source: TR-55, Eq. 2-3)

Runoff Equation (Simplified)

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 Figure 3-10. The tabular solution is reproduced below in Table 3-7. 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 3-10 Graphical Solution to the Runoff Equation (Source: TR-55)



Example 3-1:

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 inches on the x-axis and draw a line (Line 1) perpendicular to the x-axis

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

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

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

Table 3-7 Tabular Solution to the Runoff Equation (Source: TR-55)

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.

Example 3-2:

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

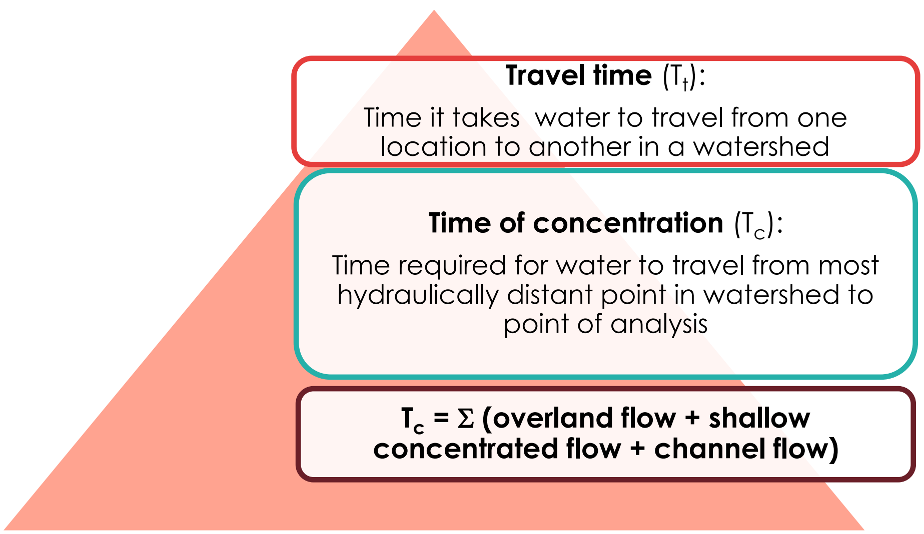
Step 2: Find CN = 80 in the second row and draw a vertical Line 2 down

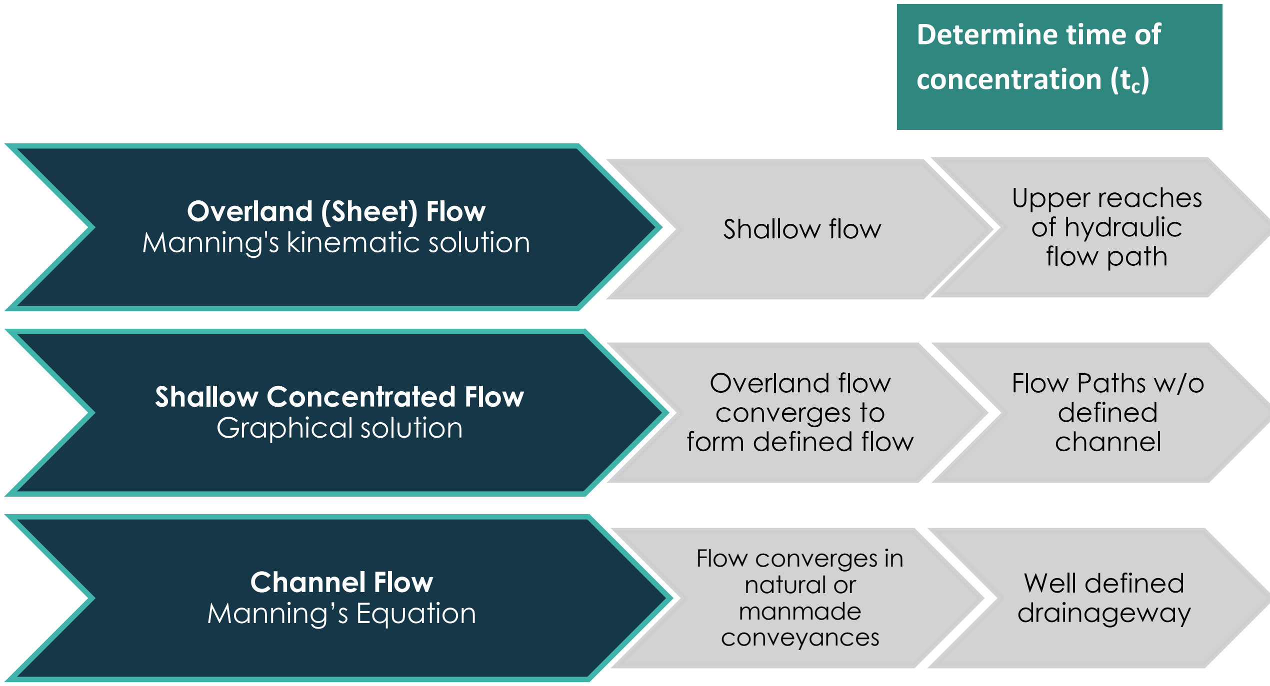
Step 3: Where Line 1 and Line 2 intersect, read the value for Q. For this example, Q = 2.04 inches.

Time of Concentration and Travel Time (Chapter 3 of TR-55)

The time of concentration, T_c, is the length of time required for a drop of water to travel from the most hydraulically distant point in the watershed or sub-watershed to the point of analysis. The travel time, T_t, is the time it takes that same drop of water to travel from the study point at the bottom of the sub-watershed to the study point at the bottom of the whole watershed. The travel time, T_t, is descriptive of the sub-watershed by providing its location relative to the study point of the entire watershed.

Similar to the rational method, the time of concentration, T_c, plays an important role in developing the peak discharge for a watershed. Urbanization usually decreases the T_c, which results in an increase in peak discharge. For this reason, to accurately model the watershed, the designer must be aware of any conditions which may act to decrease the flow time, such as channelization and channel improvements. On the other hand, the designer must also be aware of the conditions within the watershed which may actually lengthen the flow time, such as surface ponding above undersized conveyance systems and culverts.





Flow Segments

The time of concentration is the sum of the time increments for each flow segment present in the T_c flow path, such as overland or sheet flow, shallow concentrated flow, and channel flow. These flow types are influenced by surface roughness, channel shape, flow patterns, and slope, and are discussed below:

a. **Overland (Sheet) Flow** is shallow flow over plane surfaces. For the determination of time of concentration, overland flow usually exists in the upper reaches of the hydraulic flow path. TR-55 utilizes Manning's kinematic solution to compute Tc for overland sheet flow. The roughness coefficient is the primary culprit in the misapplication of the kinematic Tc equation. Care should be taken to accurately identify the surface conditions for overland flow. Table 3-1 in TR-55 provides selected coefficients for various surface conditions. Refer to TR-55 or the use of Manning's Kinematic Equation.

NOTE:

Sheet flow can influence the peak discharge of small watersheds dramatically because the ratio of flow length to flow velocity is usually very high.

Surface roughness, soil types, and slope will dictate the distance before sheet flow transitions into shallow concentrated flow.

TR-55 stipulates that the maximum length of sheet flow is 300 feet. Many hydrologists and geologists will argue that, based on the definition of sheet flow, 150 feet is a more typical distance before the combination of quantity and velocity create shallow concentrated flow. In an urban application (usually a relatively small drainage area), the flow time associated with 300 feet of sheet flow will result in a disproportionately large segment of the total time of concentration for the watershed. This will result in a large overall Tc, and may not be representative of the drainage area as a whole.

The designer should select a flow path that is not only the most hydrologically remote flow path, but also must consider the relative homogeneity of the watershed.

Manning's Kinematic Solution (NRCS TR-55)

$$Tt = 0.007 \times \frac{(nL)^{0.8}}{P_2^{0.5} \times s^{0.4}}$$

Tt = travel time (jr)

L = length of overland flow (feet)

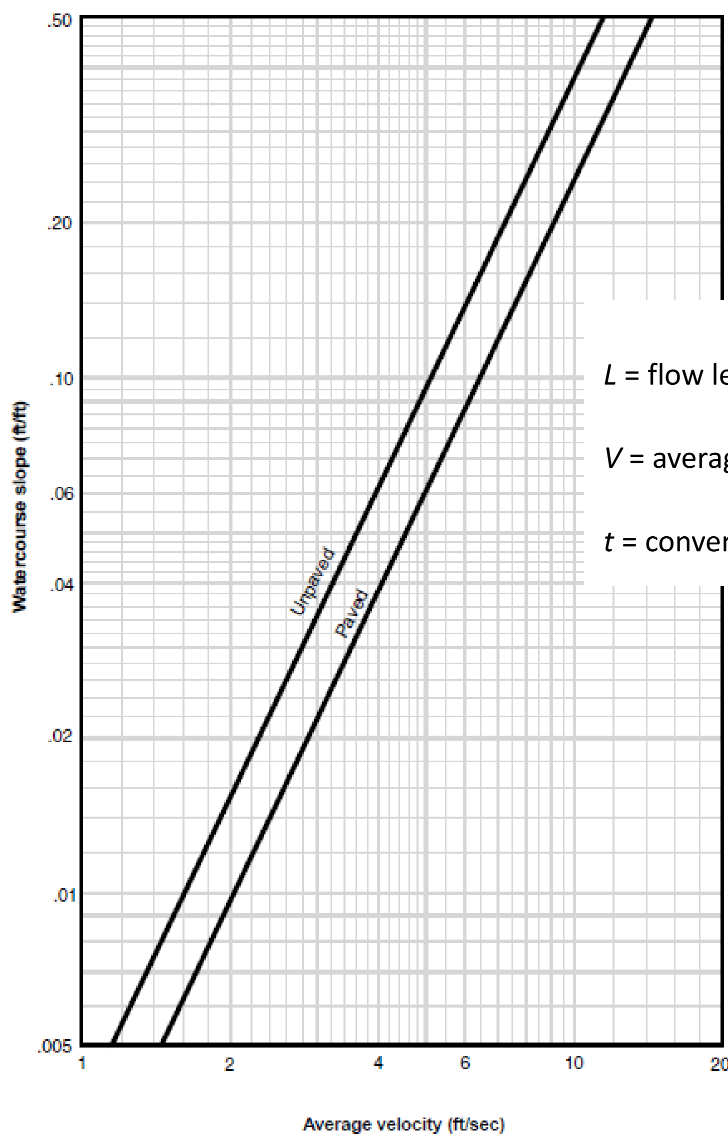
n = Manning's roughness coefficient

P_2 = 2 year, 24-hour rainfall in inches (NOAA Atlas 14)

s = slope (feet/feet)

b. **Shallow Concentrated Flow** usually begins where overland flow converges to form defined flow paths, which may include small rills or gullies. Shallow concentrated flow can exist in natural depressional features, small manmade drainage ditches (paved and unpaved) and in curb and gutters. TR-55 provides a graphical solution for shallow concentrated flow. Typically there is <u>not a well-defined channel cross-section</u>. The input information needed to solve for this flow segment is the land slope and the surface condition (paved or unpaved).

Figure 3-1 Average velocities for estimating travel time for shallow concentrated flow



$$Tt = \left(\frac{L}{V \times t}\right)$$

L = flow length (feet)

V = average velocity (feet/second)

t = conversion factor

c. **Channel Flow** occurs where flow converges in gullies, ditches or swales, and natural or manmade water conveyances (including storm drainage pipes). Channel flow is assumed to exist in perennial streams or wherever there is a well-defined channel cross-section. The Manning Equation is used for open channel flow and pipe flow, and usually assumes full flow or bank-full velocity. Manning coefficients can be found in Table 4-9(b-d) of TR-55 for open channel flow (natural and man-made channels) and closed channel flow. Coefficients can also be obtained from standard textbooks such as Open Channel Hydraulics or Handbook of Hydraulics.

$$V = \frac{1.49}{n} \times R^{(2/3)} \times \sqrt{s}$$

Manning's Equation

V = velocity (fps)

n = Manning's roughness coef.

R = hydraulic radius (A/P)

A= wetted cross sectional area

P=wetted perimeter(ft)

$$Tt = \left(\frac{L}{V}\right)$$

L = channel flow length (feet)

V = average velocity(feet/second)

→ *use Manning's equation*

Worksheet 3 from TR-55 (reproduce below in Figure 3-11) provides an organized method for documenting inputs and computations for Time of Concentration (T_c) and Travel Time (T_t).

Figure 3-11 Worksheet 3 Time of Concentration or Travel Time (Source TR-55)

Worksheet 3: Time of Concentration (T_c) or travel time (T_t)

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed

Check one: ☐ T_c ☐ T_t through subarea

Notes: Space for as many as two segments per flow type can be used for each worksheet. Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to Tc only)

Segment ID		
1. Surface description (table 3-1)		
2. Manning's roughness coefficient, n (table 3-1)		
3. Flow length, L (total L † 300 ft) .... ft		
4. Two-year 24-hour rainfall, P_2 .... in		
5. Land slope, s .... ft/ft		

6. $T_t = \dfrac{0.007\ (nL)^{0.8}}{P_2^{\ 0.5}\ s^{0.4}}$ Compute T_t .... hr ☐ + ☐ = ☐

Shallow concentrated flow

Segment ID		
7. Surface description (paved or unpaved)		
8. Flow length, L ....ft		
9. Watercourse slope, s .... ft/ft		
10. Average velocity, V (figure 3-1) .... ft/s		

11. $T_t = \dfrac{L}{3600\ V}$ Compute T_t .... hr ☐ + ☐ = ☐

Channel flow

Segment ID		
12. Cross sectional flow area, a .... ft²		
13. Wetted perimeter, p_w .... ft		
14. Hydraulic radius, $r = \dfrac{a}{p_w}$ Compute r .... ft		
15 Channel slope, s .... ft/ft		
16. Manning's roughness coefficient, n		
17. $V = \dfrac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ....ft/s		
18. Flow length, L .... ft		

19. $T_t = \dfrac{L}{3600\ V}$ Compute T_t .... hr ☐ + ☐ = ☐

20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) .... Hr ☐

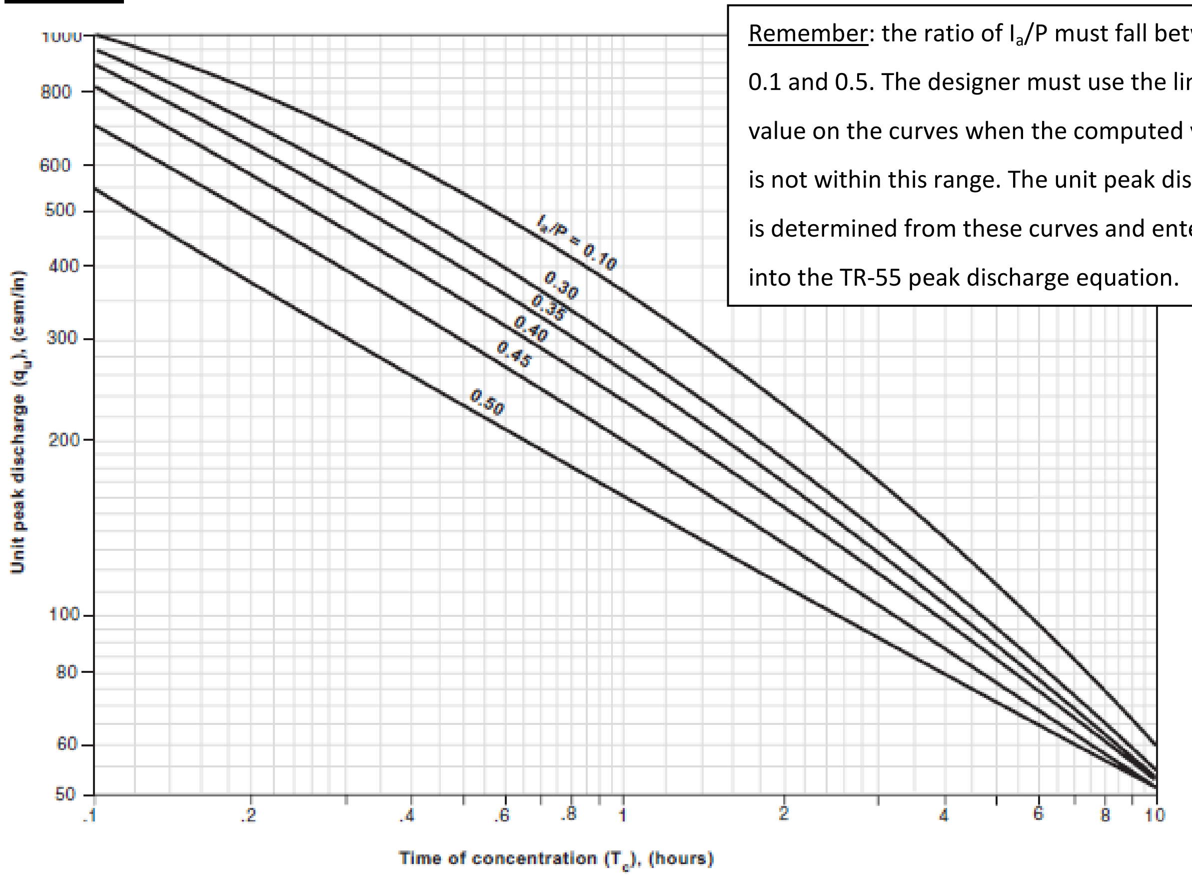
Figure 3-12 Unit Peak Discharge (q_u) for Type II Rainfall Distribution (Source TR-55)

Compute I_a/P ratio

Use t_c and I_a/P to find find q_u from chart

Find qu on chart:

Exhibit 4-II Unit peal discharge (q_u) for NRCS (SCS) type II rainfall distribution



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.

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**

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 (TR-55 chart reproduced above). The unit peak discharge is expressed in cubic feet per second per square mile per inch of runoff (cfs/mi^2/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. Exhibit 4-II (reproduced in Figure 3-12) is used for most 24-hour rainfall distributions in Virginia, except for a portion of southeastern Hampton Roads where Exhibit 4-III applies (portions of the Cities of Chesapeake, Norfolk, Portsmouth, Suffolk, and Virginia Beach). See Fig.3-7 above or Appendix B of TR-55 to confirm which rainfall distribution applies to the project under design and review.

Calculate Peak Discharge

TR-55 Peak Discharge Equation

$$q_p = q_u \times A_m \times Q \times F_p$$ (Source: TR-55, Eq. 4-1)

q_p = peak discharge (cfs)
q_u = unit peak discharge (cfs/mi²/in or csm/in)
A_m = drainage area (mi²)
Q = runoff (in)
F_p = pond and swamp adjustment factor

Table 3-8 Pond and Swamp Adjustment Factor (Source: TR-55)

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

The **pond and swamp adjustment factor (Fp)** 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 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 Table 3-8).

Worksheet 4 from TR-55 (Figure 3-13 below) provides a succinct and organized format for documenting inputs and calculating the results for the graphical peak discharge method.

Pond/swamp adjustment factor (Fp) I_a/P ratio	Combine all and calculate peak discharge (qp)

Figure 3-13 Worksheet 4 Graphical Peak Discharge Method (Source TR-55)

Worksheet 4: Graphical Peak Discharge method

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed

1. Data

Drainage area .... A_m = ______________ mi² (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 mi² 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	ft³/s			

(Where $q_p = q_u A_m Q F_p$)

Tabular Hydrograph Method (Chapter 5 of TR-55)

The tabular hydrograph method 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 which will provide more accurate and detailed results.

The reader is encouraged to review the TR-55 manual to become familiar with 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.

- 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)

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 of a curve. However, the tabular method provides this information in the form of a table of values, found in TR-55, Exhibit 5. 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 the TR-55 manual. 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:

$$q = q_t \times A_m \times Q$$

(Source: TR-55, Eq. 5-1)

Tabular Hydrograph Peak Discharge Equation

Where:

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_m = drainage area of individual subarea, mi^2
Q = runoff, in.

The product of A_m x Q is multiplied by each table value in the appropriate unit hydrograph in TR-55 Exhibit 5 (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 then 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:
The preceding discussion on the Tabular Method is taken from TR-55 and is **NOT** complete. The designer should obtain a copy of TR-55 and learn the procedures and limitations outlined in that document. Examples and worksheets, provided in TR-55, guide the reader through the procedures for each chapter.

3c5. Storage Volume for Detention Basins (Chapter 6 of TR-55)

Chapter 6 of TR-55 discusses ways to control peak discharges by delaying runoff through detention or attenuation. It also includes a simplified procedure for estimating the storage volume required to maintain peak discharges to a specified level.

Detention is the most widely used measure for controlling peak discharges. It is generally the least expensive and most reliable of the measures that have been considered. It can be designed to fit a variety of sites and accommodate spillways to meet requirements for control of outflow for multiple events. Chapter 6 contains a manual method for estimates of the effects of detention on peak discharge. The method is based on average storage and routing and is suitable for estimating required storage for preliminary design or plan review, but it is **not** a suitable method for final design of a detention basin.

Figure 6-1 of TR-55 relates two ratios: peak outflow to peak inflow discharge (q_o/q_i) and storage volume runoff volume (V_s/V_r) for all rainfall distributions. The relationships in Figure 6-1 were determined on the basis of single stage outflow devices. Some were controlled by pipe flow, others by weir flow. Verification runs were made using multiple stage outflow devices, and the variance was similar to that in the base data. The method can therefore be used for both single- and multiple-stage outflow devices. The only constraints are that each stage requires a design storm and a computation of the storage required for that design storm, and that the discharge of the upper stages includes the discharge of the lower stages.

The brevity of the procedure allows the designer or plan reviewer to examine many combinations of detention basins. When combined with the Tabular Hydrograph method, the procedure's usefulness is increased. Its principal use is to develop preliminary indications of storage adequacy and to allocate control to a group of detention basins.

Limitations

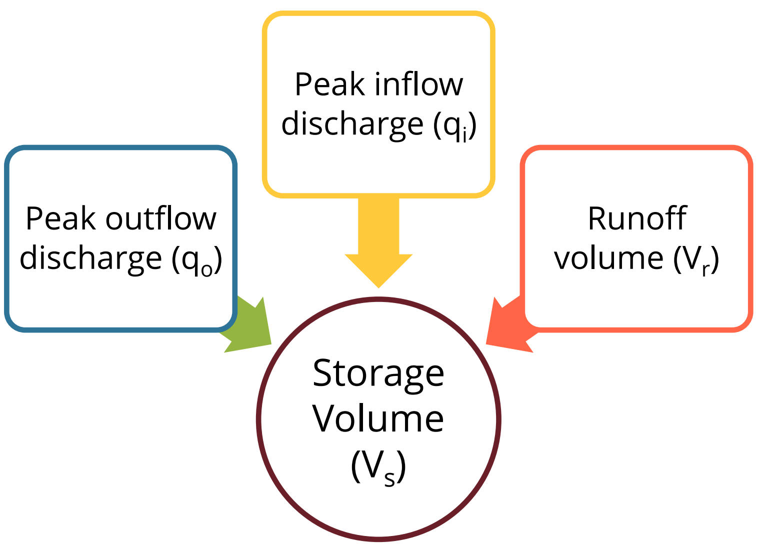
1. This routing method is less accurate as the q_o/q_i ratio approaches the limits shown in Figure 3-14. The curves in Figure 3-14 depend on the relationship between available storage, outflow device, inflow volume, and shape of the inflow hydrograph.
2. When storage volume (V_s) required is small, the shape of the outflow hydrograph is sensitive to the rate of the inflow hydrograph.
3. Conversely, when V_s is large, the inflow hydrograph shape has little effect on the outflow hydrograph. In such instances, the outflow hydrograph is controlled by the hydraulics of the outflow device and the procedure yields consistent results.

4. When the peak outflow discharge (q_o) approaches the peak flow discharge (q_i), parameters that affect the rate of rise of a hydrograph, such as rainfall volume, CN, and T_c, become especially significant.
5. The procedure should not be used to perform final design if an **error in storage of 25 percent** cannot be tolerated. Figure 3-14 is biased to prevent undersizing of outflow devices, but it may significantly overestimate the required storage capacity.

Information Needed

Use Figure 3-14 below (Figure 6-1 of TR-55) to estimate 1) the storage volume (V_s) required to detain to an allowable peak outflow, or 2) the peak outflow discharge (q_o) for a given storage volume provided. The most frequent application is to estimate V_s, which requires the following information: runoff volume (V_r), allowable peak outflow discharge (q_o), and peak inflow discharge (q_i). To estimate the q_o for a given storage volume, the required inputs are runoff volume (V_r), estimate storage volume (V_s), and peak inflow discharge (q_i).

Information needed to estimate storage volume (V_s):



Design Procedure

To estimate V_s, storage volume required, use the following procedure:

1. Determine q_o. Many factors may dictate the selection of allowable peak outflow discharge. The most common is to limit downstream discharges to a desired level, such as predevelopment discharge.
2. Estimate q_i by procedures above (Chapters 4 or 5 of TR-55). Do <u>not</u> use peak discharges developed by other procedure. When using the Tabular Hydrograph method to estimate q_i for a subarea, only use peak discharge associated with $T_t = 0$.
3. Compute (q_o/q_i) and determine value for (V_s/V_r) from Figure 3-14:

   <u>Step 1</u>: Start on the x-axis at value for (q_o/q_i) and draw a vertical Line 1 perpendicular to the x-axis until the line intersects the curve for the appropriate storm distribution type (Types II or III for Virginia).

   <u>Step 2</u>: At the intersection of Line 1 and the curve, draw a horizontal Line 2 parallel to the x-axis until you intersect the y-axis. The value where Line 2 intersects the y-axis is (V_s/V_r).

4. Q (in inches) was determined when computing q_i in step 2, but now it must be converted to the units in which V_s is to be expressed—most likely, acre-feet or cubic feet.
5. Use the results of steps 3 and 4 to compute Vs:

$$V_S = V_r \times \left(\frac{V_S}{V_r}\right)$$

(Source: TR-55, Eq. 6-2)

V_r = runoff volume (acre-ft)
V_s = storage volume required (acre-ft)
(V_s/V_r) from Figure 3-14

6. The stage in the detention basin corresponding to V_s must be equal to the stage used to generate q_o. In most situations a minor modification of the outflow device can be made. If the device has been preselected. repeat the calculations with a modified q_o value.

Worksheet 6a from TR-55 is useful for documenting inputs and results of estimating storage volume required, V_s.

To estimate peak outflow (q_o) for a given storage volume, use the following procedure:

1. Determine V_s. If the maximum stage in the detention basin is constrained, set V_s by the maximum permissible stage.
2. Compute Q (in inches) by the procedures above from Chapter 2 of TR-55, and convert to the same units as V_s (see step 4 in "estimating V_s").
3. Compute (V_s/V_r) and determine the value (q_o/q_i) from Figure 3-14:

   <u>Step 1</u>: Start on the y-axis at value for (V_s/V_r) and draw a horizontal Line 1 perpendicular to the y-axis until the line intersects the curve for the appropriate storm distribution type (Types II or III for Virginia).

   <u>Step 2</u>: At the intersection of Line 1 and the curve, draw a vertical Line 2 parallel to the y-axis until you intersect the x-axis. The value where Line 2 intersects the x-axis is (q_o/q_i).

4. Estimate q_i by the procedures presented previously from Chapters 4 or 5 of TR-55. Do not use discharges developed by any other method. When using Tabular method to estimate q_i for a subarea, use only the peak discharge associated with $T_t = 0$.
5. From steps 3 to 4, compute q_o:

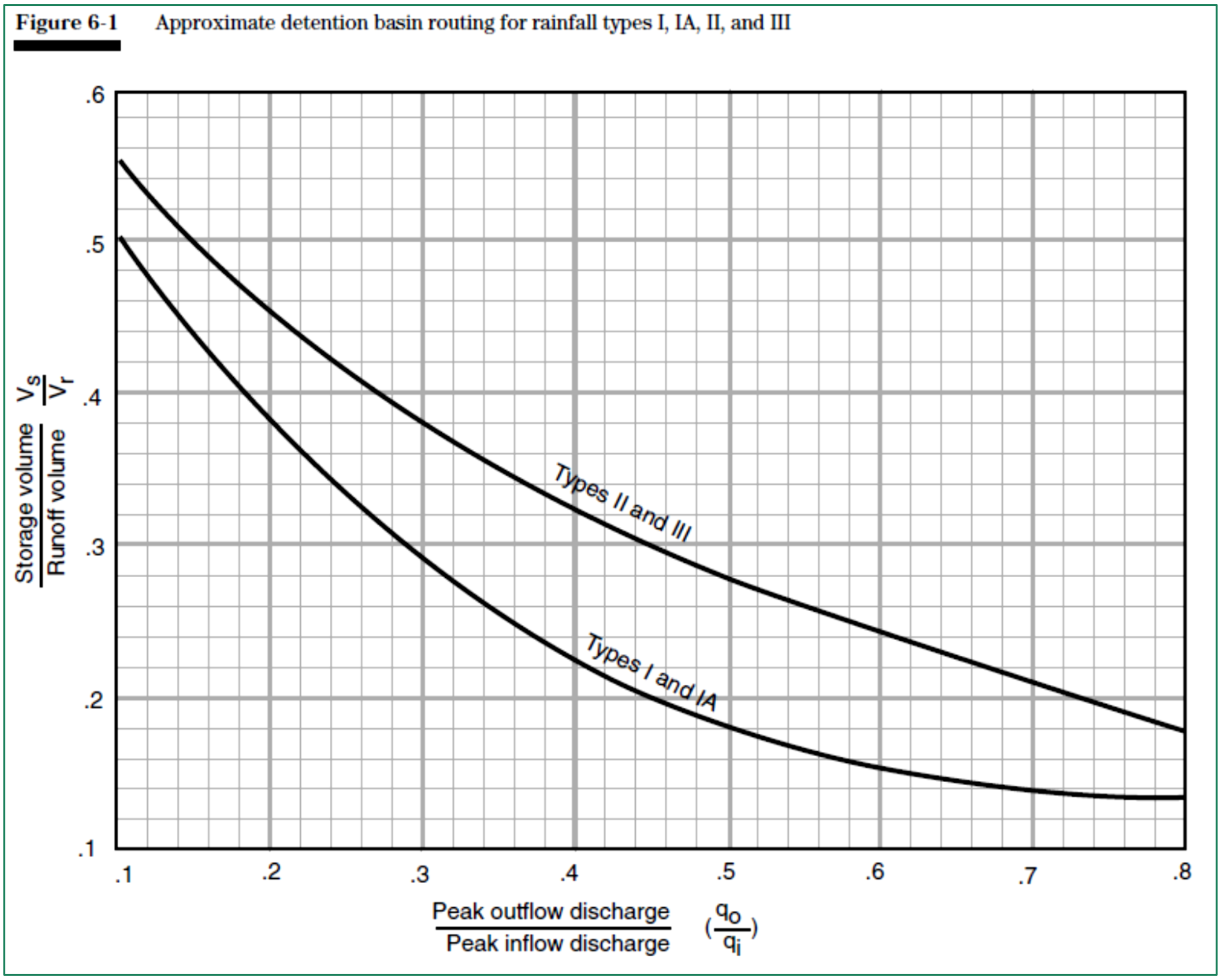
$$q_o = q_i \times \left(\frac{q_o}{q_i}\right)$$ (Source: TR-55, Eq. 6-3)

   q_o = peak outflow (cfs)
   q_i= peak inflow (cfs)
   (qo/qi) from Figure 3-14

6. Proportion the outflow device so that the stage at q_o is equal to the stage corresponding to V_s. If q_o cannot be calibrated except in discrete steps (i.e., pipe sizes), repeat the procedure until the stages for q_o and V_s are approximately equal.

Worksheet 6b from TR-55 is useful for documenting inputs and results of estimating peak outflow (q_o) for a given storage volume.

Figure 3-14 Approximate Detention Basin Routing (Source: TR-55)



Example: Estimate Storage Volume

Given the following:

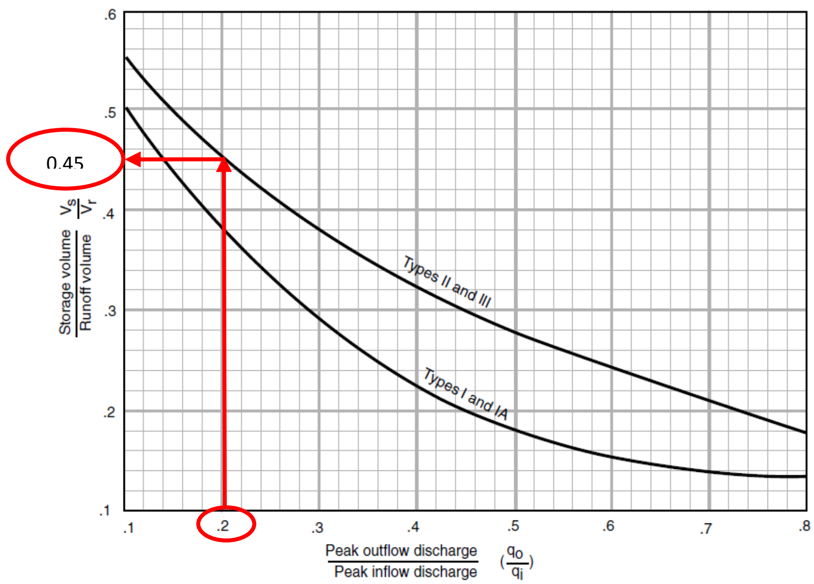
- 3 acre site in Richmond, Virginia (Type II rainfall distribution)
- Post-development discharge rate into basin (q_i) = 10 cfs
- Allowable discharge rate (q_o) = 2 cfs
- Post-development runoff volume (V_r) = 1.33 inches

Estimate Storage Volume:

1. Compute (q_o/q_i): $\frac{q_o}{q_i} = \frac{2\ cfs}{10\ cfs} = 0.2$

2. Using Figure 3-14 above, determine (V_s/V_r) from the Type II rainfall distribution curve:

$\frac{\boldsymbol{V_S}}{\boldsymbol{V_r}} = \mathbf{0.45} \pm$



3. Convert runoff volume (V_r) from inches to cubic feet (units in which V_s is to be expressed):

$$V_r = 3\ acres \times 1.33\ inches = 4\ acre\text{-}inches \times \frac{1\ foot}{12\ inches} \times \frac{43{,}560\ ft^2}{1\ acre} = 14{,}520\ ft^3$$

4. Compute V_s:

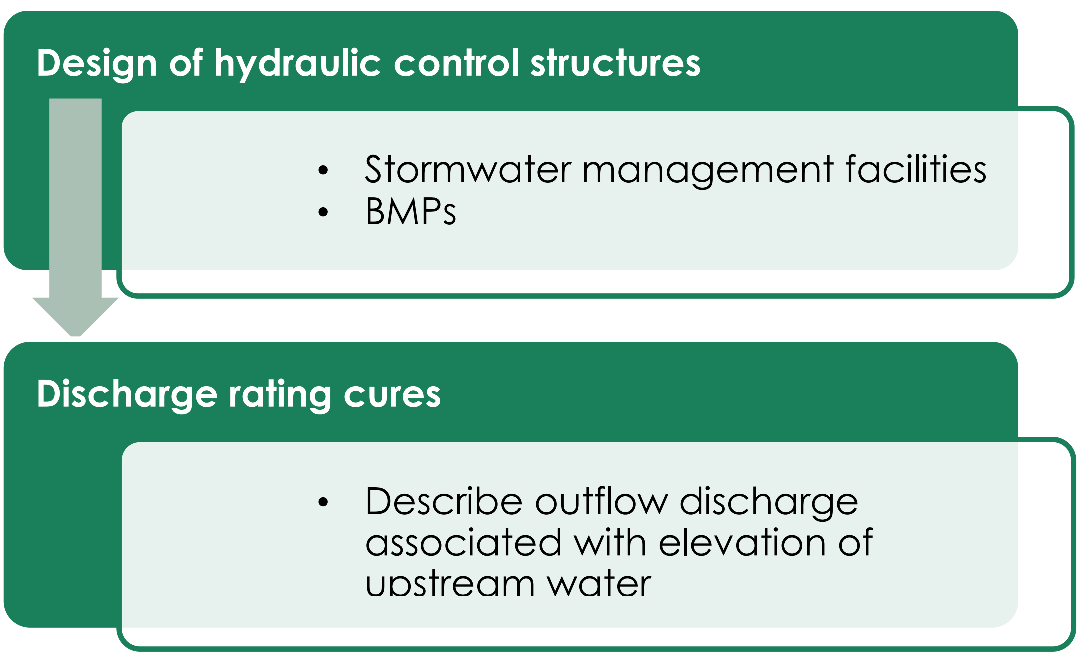
$$V_s = V_r \times \left(\frac{V_s}{V_r}\right) = 14{,}520\ ft^3 \times 0.45 = 6{,}534 ft^3$$

REMEMBER:

Typical error is ±25% so this procedure can be useful for **ESTIMATION** but should **not** be used for final design if error cannot be tolerated.

3c6. Hydraulic Control Design

The design of hydraulic control structures for stormwater management facilities and BMPs, such as principal and auxiliary spillways, requires generating discharge rating curves that describe the outflow discharge associated with the elevation or stage of the water surface elevation upstream of the structure. The discharge rating curve is critical for routing storm events through the facility or BMP to confirm that adequate detention is achieved. Hydraulic structures can be complex to model, as discussed in Chapter 5 of the VSWMH (1999 edition), especially for multi-stage risers that provide control for water quality, stream channel erosion, and flooding control. For the purpose of this Participants Guide, the focus will be specifically on the use and design of simple weirs and orifices. More detailed information on hydraulic control structures can be found in the Handbook of Hydraulics by Brater and King, Open Channel Hydraulics by Chow, the Hydraulic Design Handbook by Mays, and many other suitable texts on hydraulics and fluid mechanics.



Weir Equation

A weir is defined as a structure placed across a waterway or waterbody for regulating or measuring flow or discharge from the body. Common examples of weir include overflow spillways, box or pipe riser crests, or vegetated auxiliary spillways. The weir equation is used to generate a discharge rating curve. Weir types can include rectangular, trapezoidal, or other geometries. The basic weir equation, if rearranged, allows for design of the weir length based on an allowable discharge. The information required for input includes a dimensionless weir coefficient (C_w), the hydraulic head (h), the length of the weir (L), or the allowable peak discharge (Q_a).

$$Q_w = C_w \times L \times h^{1.5}$$

Weir Equation

$$L = \frac{Q_a}{C_w \times h^{1.5}}$$

Rearranged Weir Equation

Where:
- Q_w = weir discharge, cfs
- Cw = dimensionless weir coefficient (see Table 3-9)
- L = length of weir, ft
- h = hydraulic head (difference between water surface elevation and weir crest), ft
- Q_a = allowable weir discharge, cfs

Table 3-9 below provides dimensionless weir coefficients for a rectangular weir. The weir coefficient can vary based upon the breadth of the weir crest and the hydraulic head. Weir breadth is generally consistent and reflected in the selection of the coefficient, but the hydraulic head varies throughout the basin routing as water surface elevation changes. While the weir coefficient is generally fixed based upon the breadth, the variability for hydraulic head is not always used in developing the discharge rating curve for a weir due to complexity. It is common to find a single weir coefficient used for all hydraulic depths for simplified rating curve development, with the coefficient chosen based upon the design head for the allowable peak discharge. Some computer models allow for variability of the weir coefficient with water surface elevation.

Table 3-9 Dimensionless Weir Coefficients (Source: VSWMH, 1999)

WEIR FLOW COEFFICIENTS, C			
Measured head, *h*, (*ft.*)	**Breadth of weir crest (*ft.*)**		
	0.50	**0.75**	**1.00**
0.2	2.80	2.75	2.69
0.4	2.92	2.80	2.72
0.6	3.08	2.89	2.75
0.8	3.30	3.04	2.85
1.0	3.32	3.14	2.98
1.2	3.32	3.20	3.08
1.4	3.32	3.26	3.20
1.6	3.32	3.29	3.28
1.8	3.32	3.32	3.31
2.0	3.32	3.32	3.30
3.0	3.32	3.32	3.32
4.0	3.32	3.32	3.32
5.0	3.32	3.32	3.32

Orifice Equation

An orifice is another type of structure used to control or measure discharge, and is generally defined as an opening or a constriction. Orifices are generally round in shape, but other geometric arrangement can be found, including rectangular orifices. An orifice can work as a weir until it is submerged and can be modeled as described above. However, the orifice equation is used to generate the discharge rating curve when the orifice is fully submerged, which is generally how an orifice is designed to operate.

The orifice equation, if rearranged, allows for design of the orifice area based on an allowable discharge. The information required for input includes a dimensionless orifice coefficient (C), the hydraulic head (h), the value for gravitational acceleration (g), the area of the orifice (a), the orifice discharge (Q), or the allowable peak discharge (Q_a).

$$Q = C \times a \times \sqrt{2 \times g \times h}$$

Orifice Equation

$$a = \frac{Q}{C \times \sqrt{2 \times g \times h}}$$

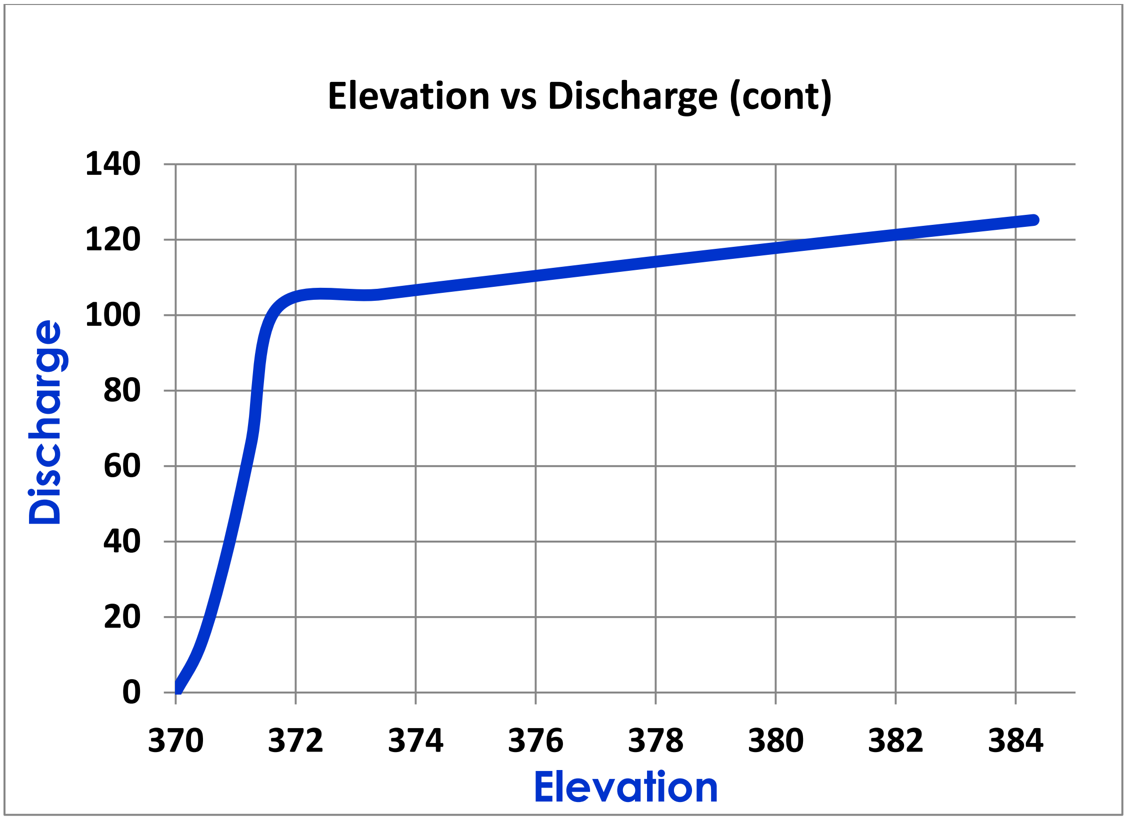
Rearranged Orifice Equation

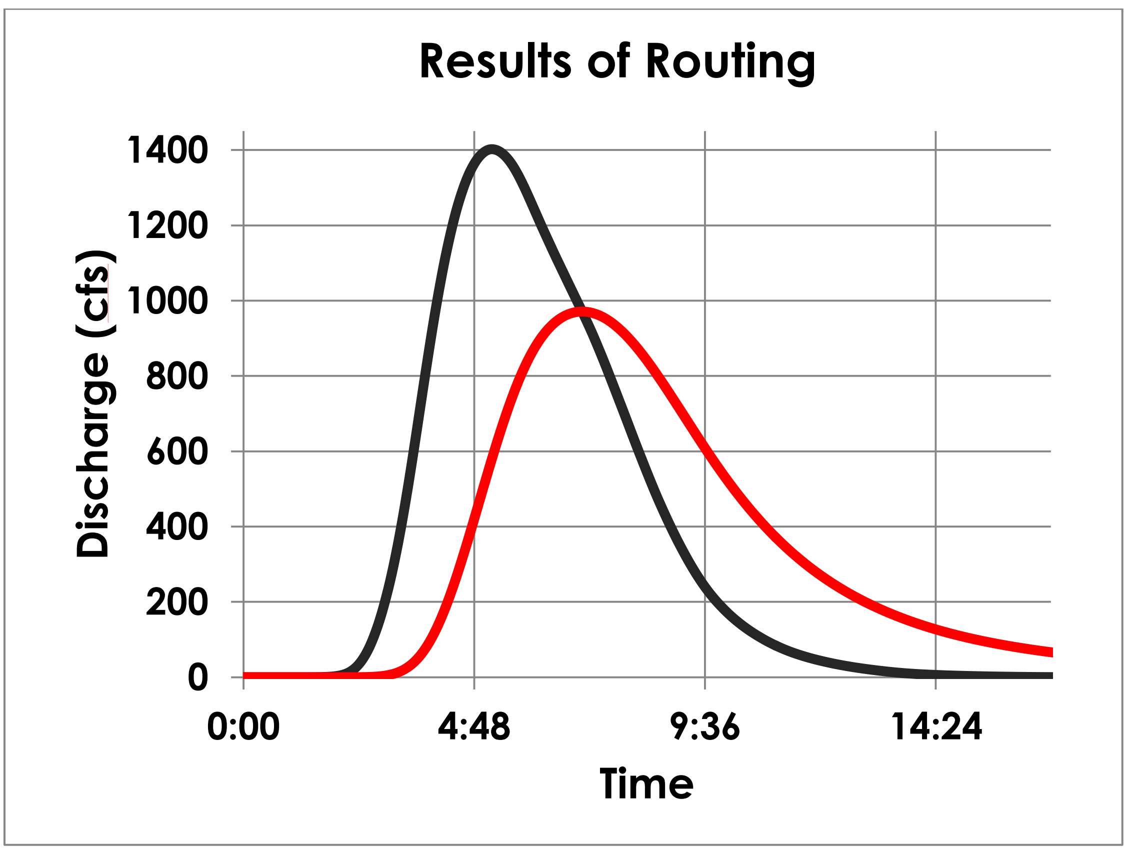
Where:

Q = orifice discharge, cfs
C = dimensionless orifice coefficient
a = orifice area, ft^2
g = gravitational acceleration, 32.2 ft/sec^2
h = hydraulic head, ft
Q_a = allowable peak discharge, cfs

An orifice coefficient value of **0.6** is commonly used in simplified calculations, especially for round orifices. More detailed dimensionless orifice coefficients are included in the hydraulic references in the introduction to this section.

The area (a) of an orifice can be determined using basic geometric principles for round and rectangular shapes. See Chapter 5 of the VSWMH (1999 edition) for more information.


Elevation vs Discharge (cont)
140
120
100
80
60
40
20
0
Discharge
370
372
374
376
378
380
382
384
Elevation


Results of Routing
1400
1200
1000
800
600
400
200
0
Discharge (cfs)
0:00
4:48
9:36
14:24
Time

3d. Water Quality

3d1. The Simple Method

The Regulations require the use of the Virginia Runoff Reduction Method (or another Board approved method) to evaluate compliance with the Part II B water quality criteria for new development and redevelopment (9VAC25-870-63 A). The Virginia Runoff Reduction Method uses the Simple Method (modified to include impervious, managed turf and forest/open space) to calculate the phosphorus load expected to leave a site *based on landcover conditions.* The Simple Method calculated the **annual** pollutant (phosphorus) load exported in stormwater runoff from small urban catchments.

$$L = P \times P_j \times Rv \times C \times A \times 2.72/12$$

L	= total post-development pollutant load (pounds/ year)
P	= average annual rainfall depth (inches) = 43 inches for Virginia
P_j	= fraction of rainfall producing runoff = 0.9
Rv	= volumetric runoff coefficient
C	= flow-weighted event mean concentration (EMC) of TP (mg/L) = 0.26 mg/L
A	= area of the development site (acres)
2.72	= unit conversion factor: L to ft^3, mg to lb, and acres to ft^2
12	= unit conversion factor: rainfall inches to feet

$$Rv_{composite} = (Rv_I \times \%I) + (Rv_T \times \%T) + (Rv_F \times \%F)$$

$Rv_{composite}$ =	Composite or weighted runoff coefficient
Rv_I =	Runoff coefficient for Impervious cover (0.95)
Rv_T =	Runoff coefficient for Turf cover or disturbed soils
Rv_F =	Runoff coefficient for Forest/Open Space
$\% I$ =	Percent of site in Impervious cover (fraction)
$\%T$ =	Percent of site in Turf cover (fraction)
$\%F$ =	Percent of site in Forest/Open Space (fraction)

3d2. Treatment Volume and Stormwater Practice Sizing

The Treatment Volume (Tv) is the new regulatory equivalent of the water quality volume (WQv). The WQv is still considered the water quality design standard for grandfathered projects (Part IIC) and is defined as the *first 1/2 inch of runoff multiplied by the impervious surface of the land development project*. Like many of the standards upon which stormwater practices are based, the research on local rainfall distribution patterns, storm size, and the "first flush" phenomenon has resulted in a gradual change in the definition of the water quality storm and design treatment volume.

The definition of the Tv is the volume of runoff from the contributing drainage area generated by the rainfall from the 90th percentile storm event. The figure below represents the rainfall from the rain gauges at Regan Washington National Airport. The average rainfall from Reagan Washington Airport, Richmond Airport, and the cities of Harrisonburg, Lynchburg, and Bristol provide an average 90th percentile rainfall depth of one inch.

> The Treatment Volume (Tv) is equal to the runoff volume from the contributing drainage area generated by a one-inch rainfall.

90th Percentile Rainfall Depth at Reagan Washington National Airport

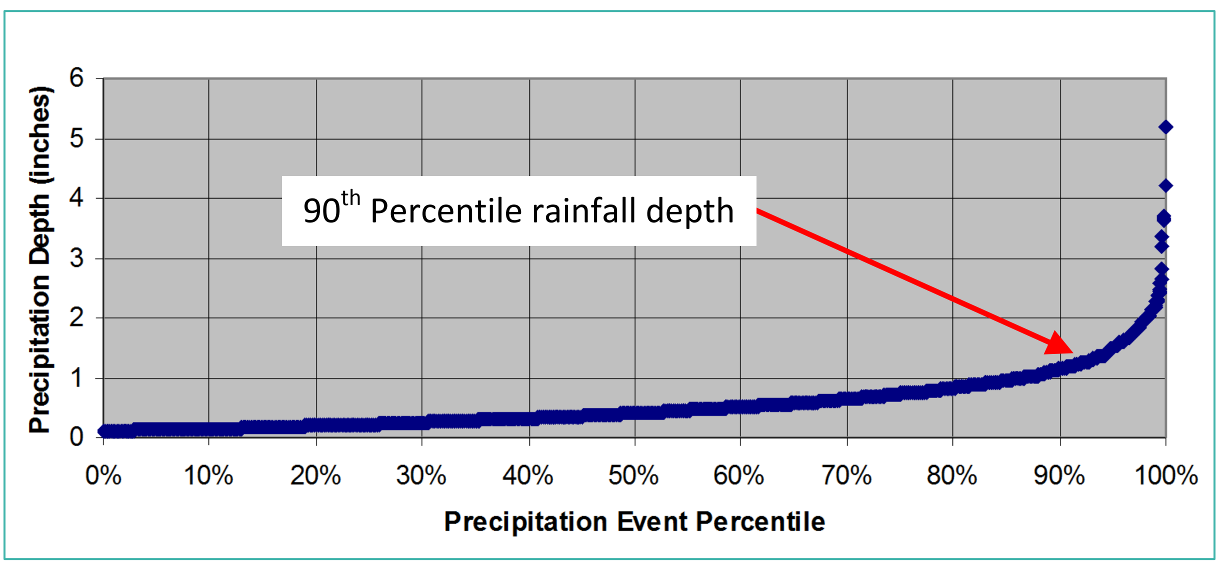


Figure. 3-15. 1" annual average: Reagan Washington Nat., Richmond Intern. Airports, Harrisonburg, Lynchburg, Bristol

This 90th percentile rainfall depth is based on the performance goal of stormwater practices achieving an ***annual*** volume and ***annual*** load reduction. That is, 90% of all rainfall events are 1-inch or less in depth. So any stormwater practices designed to manage the runoff from this rainfall will be managing 90% of all storm events, and the first inch of those storms that exceed 1-inch. This corresponds to approximately 70% of the annual rainfall (meaning that a small number of larger storms contribute a disproportionate amount of rainfall ~ 30%).

The selection of 90^{th} percentile corresponds nicely with the inflection point of the rainfall event curve; meaning that it represents an optimal target rainfall depth (selecting a larger storm event or a higher percentile would not greatly increase the annual volume captured, but would certainly increase the cost of implementation).

There are some important distinctions related to the new Tv standard:

- The management of the 1-inch rainfall event provides for an ***annual*** treatment, or better referred to as **Annual Volume Reduction** and **Annual Load Reduction**. The annual reduction represents an average over all storms and not individual single-event modeled storms. This means that oversizing a practice does not necessarily provide for an increase in performance (unless the entire Level 2 upgrade is included; to be discussed further in Module 6);
- Stormwater practice sizing rules are based on the particular BMP. Some BMPs will include a storage volume component that must be sized to capture the Tv. These include Bioretention, Permeable Pavement, Wet Ponds, etc. Others BMPs are sized to manage this volume as a flow through practice and must be sized according to the sizing rules provided in the BMP Design Specifications. In either case, the contributing drainage area to the stormwater practice will have a composite Rv that will be used to design the BMP, referred to as Tv_{BMP} based on the following formula:

$$Tv_{BMP} = \frac{(P \times Rv_{composite} \times A)}{12}$$

Tv_{BMP} = Design Treatment Volume from the contributing drainage area to the stormwater practice (does not include remaining runoff from upstream practices)

P = 90^{th} Percentile rainfall depth = 1”

$Rv_{composite}$ = Composite runoff coefficient (equation shown above)

A = Contributing drainage area to the stormwater practice.

The volume of runoff is now the result of the runoff contribution from the entire drainage area based on the weighted Rv or $Rv_{composite}$, and not just the impervious areas using a single Rv of 0.95.

The Tv_{BMP} is the primary sizing parameter for the stormwater practice. However, when using a treatment train, the designer should consult the spreadsheet to determine the total Tv to (directly from immediate contributing drainage area, and any additional volume remaining from the upstream BMP.

3e. Water Quality Treatment Volume (Tv) Peak Flow Rate

The peak flow rates for the 1-year 24-hour storm and larger are readily computed using accepted hydrologic methods. However, there has not been a standard method for computing the water quality or Treatment Volume (*Tv*) design peak flow rate. The *Tv* design peak flow rate is needed for the design and sizing of pretreatment cells, level spreaders, by-pass diversion structures, overflow riser structures, grass swales and water quality swale geometry, etc. All require a peak rate of discharge in order to ensure non-erosive conditions and flow capacity.

Of the hydrologic methods available, the Rational Formula is highly sensitive to the time of concentration and rainfall intensity, and therefore should only be used with reliable Intensity-Duration-Frequency (IDF) curves (or B, D, & E factors) for the rainfall depth and region of interest (Claytor and Schueler, 1996). Unfortunately, there are no IDF curves or B, D, & E factors available for the 1-inch rainfall depth. The NRCS *CN* methods are very useful for characterizing complex sub-watersheds and drainage areas and estimating the peak discharge from large storms (greater than 2 inches), but can significantly underestimate the discharge from small storm events (Claytor and Schueler, 1996). Since the *Tv* is based on a 1-inch rainfall, this underestimation of peak discharge can lead to undersized diversion and overflow structures, resulting in a significant volume of the design *Tv* potentially bypassing the runoff reduction practice. Undersized overflow structures and outlet channels can cause erosion of the BMP conveyance features which can lead to costly and frequent maintenance.

In order to maintain consistency in design and plan review, the following Modified *CN* Method is one method recommended for calculating the peak discharge for the 1-inch rain event. The method uses the Small Storm Hydrology Method (Pitt, 1994) and NRCS Graphical Peak Discharge Method (USDA 1986) to provide an adjusted Curve Number that is more reflective of the runoff volume from impervious areas within the drainage area. The design rainfall is a NRCS Type II distribution, so the method incorporates the peak rainfall intensities common in the eastern United States. The time of concentration is computed using the method outlined in TR-55.

(The designer and reviewer should also note the methodology for determining the appropriate Tc flow path for a small catchment to a BMP: the directly contributing drainage area homogeneity is likely that of an impervious or developed area, and therefore should be represented by a representative impervious Tc path.)

The following provides a step by step procedure for calculating the Water Quality Treatment Volume's peak rate of discharge, $\boldsymbol{q_{pTv}}$:

Step 1: Calculate the adjusted *CN* for the site or contributing drainage area.

The following equation is derived from the NRCS *CN* Method and is described in detail in the **Chapter 4** (Hydrology) of the National Engineering Handbook (NEH-4), and **Chapter 2** (Estimating Runoff) of NRCS TR-55:

Equation 1 (equation 11.11 of the VSMH): Derivation of NRCS Curve Number and Runoff Equation

$$CN = \frac{1000}{[10 + 5P + 10Q_a - 10(Q_a^2 + 1.25Q_aP)^{0.5}]}$$

Where:

CN = Adjusted curve number

P = Rainfall (inches), (1.0" in Virginia)

Q_a = Runoff volume (watershed inches), equal to $Tv \div drainage\ area$

Note: When using a hydraulic/hydrologic model for sizing a runoff reduction BMP or calculating the q_{pTv}, designers should use this modified *CN* for the drainage area to generate runoff peak flow from the *Tv* for the 1-inch rainfall event.

Step 2: Compute the site or drainage area Time of Concentration (*Tc*).

Chapter 4 of the *Blue Book*, and Chapter 3 of TR-55 (Time of Concentration and Travel Time) provide detailed procedures for computing the *Tc.* The designer should select the *Tc* flow path that is representative of the homogeneous drainage area, assumed to be primarily impervious cover.

Step 3: Calculate the Water Quality Treatment Volume's peak discharge (q_{pTv})

The (q_{pTv}) is computed using the following equation and the procedures outlined in Chapter 4 (Graphical Peak Discharge Method) of TR-55, Designers can also use WinTR-55 or an equivalent TR-55 spreadsheet to compute (q_{pTv}):

Read the initial abstraction (I_a) from TR-55 Table 4.1

Table 4-1 I_a values for runoff curve numbers

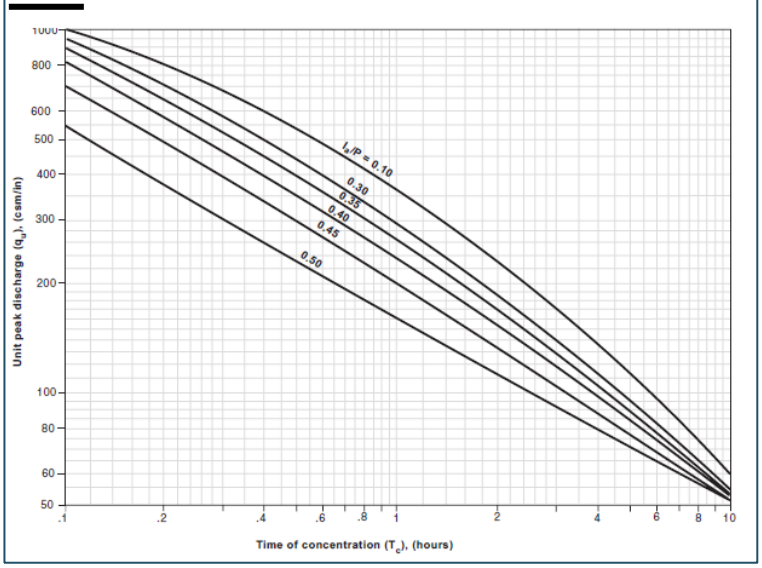
Curve number	I_a (in)	Curve number	I_a (in)
40	3.000	70	0.857
41	2.878	71	0.817
42	2.762	72	0.778
43	2.651	73	0.740
44	2.545	74	0.703
45	2.444	75	0.667
46	2.348	76	0.632
47	2.255	77	0.597
48	2.167	78	0.564
49	2.082	79	0.532
50	2.000	80	0.500
51	1.922	81	0.469
52	1.846	82	0.439
53	1.774	83	0.410
54	1.704	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		

or calculate it using $I_a = 200/CN - 2$

Compute I_a/P (P = 1.0);

Read the Unit Peak Discharge (q_u) from exhibit 4-II using Tc and I_a/P *(see also Section 3c4 in this Module)*;

Exhibit 4-II Unit peal discharge (q_u) for NRCS (SCS) type II rainfall distribution



Compute the (q_{pTv}) peak discharge:

(Equation 11.12. of the VSMH): Modified NRCS TR-55 Eq. 4-1

$$q_{pTv} = q_u \times A \times Q_a$$

q_{pTv} = Treatment Volume peak discharge (cfs)

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

A = drainage area (mi^2)

Q_a = runoff volume (watershed inches = Tv/A)

This procedure is for computing the peak flow rate for the 1-inch rainfall event. All other calculations of peak discharge from larger storm events for the design of drainage systems, culverts, etc., should use published *CN*s and computational procedures.