Module 9: Hydrology for Plan Reviewers

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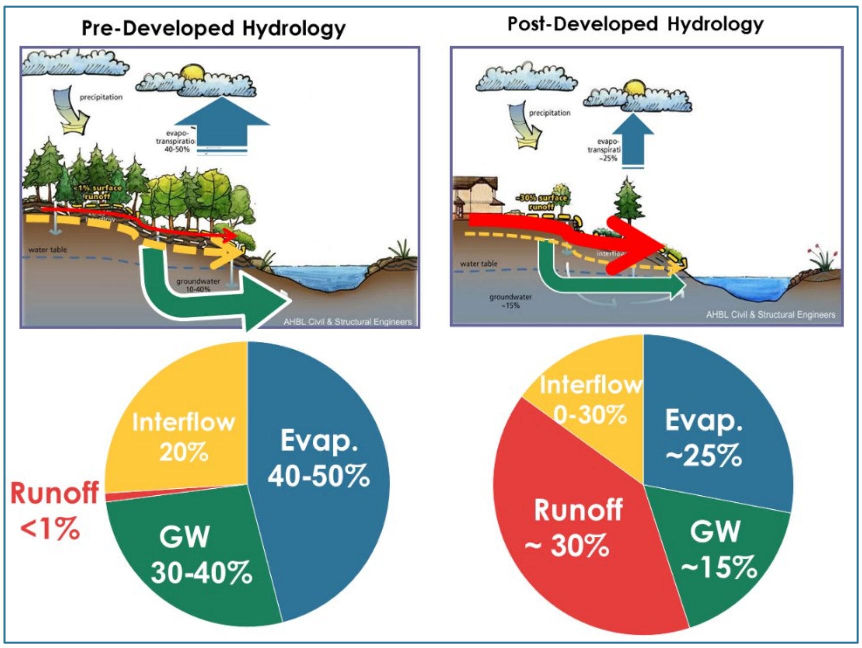
Learning Objectives

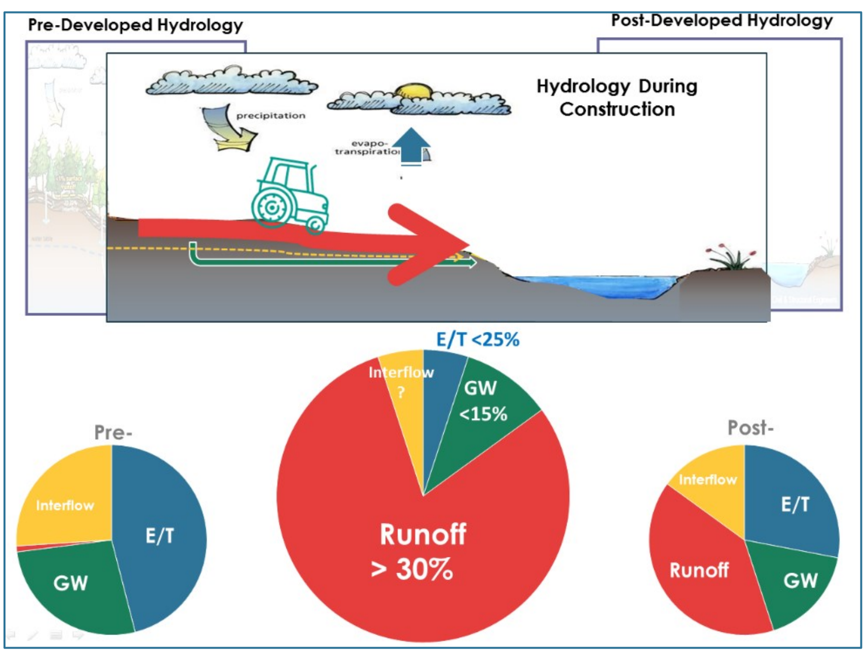
At the end of this module, you will be able to:

- Discuss basic hydrologic principles and changes to the hydrologic cycle due to construction projects and development
- State the Virginia regulatory water quantity requirements for all land-disturbing projects given the acreage or square footage of the land-disturbing activity
- Recall basic stormwater engineering concepts for estimating runoff using the Rational Method and Modified Rational Method
- Verify assumptions made to segment and calculate drainage area flow paths along with the respective flow travel times and the time of concentration
- Define travel time, time of concentration, and the three different flow types
- Determine the travel time and time of concentration for a given drainage area, provided necessary drainage area characteristics are available
- Determine the runoff coefficients for a given land use
- Calculate a weighted runoff coefficient
- Determine rainfall intensity from an Intensity-Duration-Frequency Curve
- Determine the peak rate of runoff using the Rational Method
- Explain the key principles, assumptions, and limitations associated with both the Rational and Modified Rational Method

9a. Hydrologic Cycle

Hydrology is the study of the properties, distribution, and effects of water on the earth's surface and in the soils, underlying rocks, and atmosphere. More simply put, hydrology is the study of water movement between the different water compartments on earth. The hydrologic cycle refers to the continuous circulation of water on earth as it moves from one compartment to another.



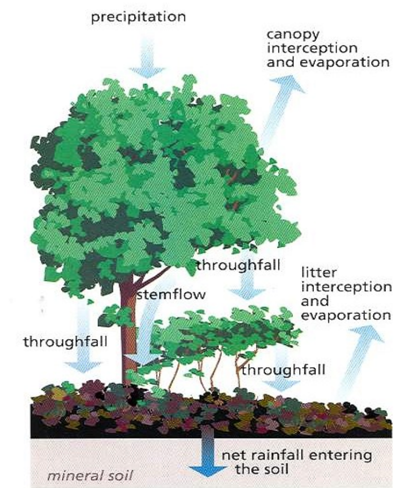


As population growth increases, the demand for buildings, homes, and infrastructure also increases. The natural hydrologic cycle can be altered at a local level, through man-made changes such as land development. Altering one component of the water cycle affects all other elements of the cycle. Roads, 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, natural drainage patterns are altered. The amount of evapotranspiration and infiltration decreases and stormwater runoff substantially increases.

Development has often led to the loss of important environmental processes that act to minimize the generation of stormwater runoff and slow its movement across surfaces:

- Reduced evapotranspiration, interception, and infiltration from the loss of vegetation;
- Removal of surface storage/ponding opportunities through smoothing or levelling of the land surface;
- Reduced infiltration from the removal of topsoil, compaction of subsoil, and laying down of impervious cover such as concrete, asphalt, building infrastructure;
- Reduced infiltration from the use of built drainage systems such as gutters, storm sewers and smooth-lined channels;
- Reduced groundwater recharge and stream base flows from increased stormwater runoff over impervious surfaces; and
- Declining watershed health from increased imperviousness.

Reduced evapotranspiration and infiltration from loss of vegetation



Under natural woodland and meadow conditions, only a small portion of annual rainfall becomes stormwater 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.

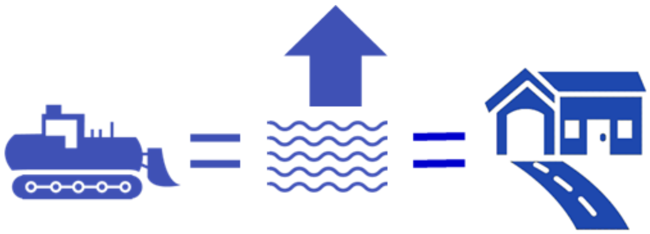
Turf grass, which is commonly used to replace natural vegetation, produces more runoff than natural open space and forestland, often because it is laid over compacted soil. Turf grass management can involve the application of large amounts of fertilizer and pesticides, which can be picked up by stormwater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

Removal of surface storage/ponding opportunities through smoothing or levelling of land surface

The buildup of organic material and the roughness of the land surface including surface depressions provide opportunities for water storage. When land is graded, surface litter layers and often soil organic matter are removed, and surface land depressions are levelled out. With this loss, stormwater is no longer able to remain on the surface until evaporation, infiltration, or absorption by soil or vegetation can occur. Instead, stormwater runoff will increase and flow unimpeded.

Reduced infiltration from removal of topsoil, compaction of subsoil, and impervious cover

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 imperative when selecting infiltration or runoff-reducing post-construction best management practices (P-BMPs).



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. Consequently, 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.

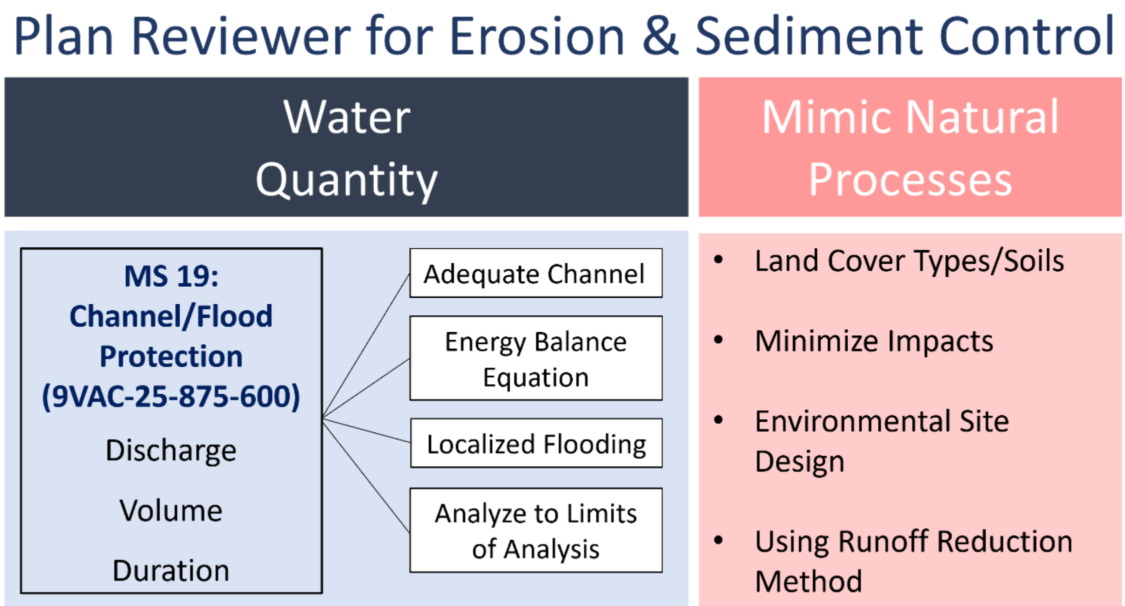
Reduced infiltration from built or traditional drainage systems

Total runoff volume can increase dramatically as a direct result of land surface changes. 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**.**

The Part V, Article 3 and Part V, Article 4 water quantity criteria address ***channel protection*** and ***flood protection*** because as stormwater runoff increases, there is a direct impact on stream channels and flooding. Combinations of greater volumes of runoff occurring more often and at higher flow rates, even in small storm events, can create:

- Altered stream flows that can affect water conditions and habitat for fish
- Channel erosion, widening and downcutting that can degrade stream habitat and produce substantial increases in sediment loads from accelerated erosion
- Increased frequency of flooding and floodplain expansion
- Entrenched streams cutoff from the flood plain


Incised Channel (Photo credit: Arlington County)



Effective stormwater management allows land development in ways that minimize impacts to existing properties and natural resources due to uncontrolled runoff. The Virginia Erosion and Stormwater Management Act (VESMA) and Regulation promote preservation and/or simulation of natural rainfall/runoff processes in meeting requirement for the control of both:

- Water quantity (in terms of restricted stormwater discharge rates and promotion of runoff volume reduction for the protection of channels and protection against flooding) and
- Water quality (in terms of restricting total phosphorus loads associated with runoff, using runoff reduction, and other treatment practices).

Maintaining the natural rate and volume of runoff to the greatest extent possible minimizes impacts to existing natural drainage systems. The remainder of this module and the next few modules highlight some of the basics of engineering-related hydrology and hydraulics that pertain to the planning and design elements of stormwater management. Hydrologic analyses use drainage area characteristics (such as size, land cover, and steepness) and precipitation data (such as intensity and duration) to quantify the volumetric flow rate of water.

These analyses determine water flow depth and velocity on a surface or at hydraulic structures and are the basis for stormwater management structure design. A basic explanation of these analyses included in this module provides the background the plan reviewer needs to effectively evaluate and review critical components of stormwater management.

Due to the complexity of the hydrologic cycle, simulating even a small portion of it, such as the relationship between precipitation and surface runoff, can be an inexact science. Many variables and dynamic relationships must be accounted for and, in most cases, reduced to basic assumptions. These assumptions were incorporated into past regulatory and computational frameworks for managing stormwater, in an effort to establish criteria that are relatively simple to implement. Unfortunately, either as a result of these assumptions or in spite of them, the resulting stormwater designs often do not meet all the program goals. The increases in the volume, duration, and frequency of peak runoff events have continued to impact streams and aquatic resources.

The Virginia Erosion and Stormwater Management (VESM) Regulation (**9VAC25-875**) attempts to address these stormwater impacts by incorporating runoff reduction (and adopting the Virginia Runoff Reduction Method, VRRM). The preferred compliance approach is to manage (and reduce to the greatest extent possible) the volume of runoff from the most frequent rainfall events as the basis for hydrologic and hydraulic designs of stormwater management strategies. In general terms, this represents the incorporation of better site design strategies (otherwise referred to as low impact development, green infrastructure, stormwater site design, etc.) into a regulatory framework built around runoff volume reduction. As with past regulations, the reduction of pollutant loads remains the chief compliance metric for those projects required to comply with the Part V, Article 3 technical criteria for both water quality and water quantity. The difference is that runoff volume reduction is now an important and, in some cases, necessary strategy to achieve the required pollutant load reductions. Runoff volume reduction is also linked with the channel and flood protection criteria (**9VAC25-875-600**) that apply to all projects subject to the VESM Regulation (**9VAC25-875**). These projects include land-disturbing activities greater than or equal to 10,000 square feet, 2,500 square feet in Chesapeake Bay Preservation Areas, or a more stringent threshold designated by local ordinance.

As discussed in Module 5, hydrologic methods, design storms, and good engineering practices must be consistent with those listed in the VESM Regulation and the Virginia Stormwater

Management Handbook (VSWHB) (**9VAC25-875-600-F, 9VAC25-875-620**). Additionally, guidance provided in the VSWHB and on the Virginia Stormwater BMP Clearinghouse (for post-construction BMPs) are considered appropriate practices.

The purpose of this module is to provide a basic review of the hydrologic principles, stormwater engineering practices, and the computational procedures that apply to the water quantity criteria in the VESM Regulation. The VSWHB, NRCS' Technical Release 55 (TR-55): Urban Hydrology for Small Watersheds, the WinTR-55 (2006) User's Guide, and the National Engineering Handbook can also serve as important resources for plan reviewers.

9c. Understanding the Water Quantity Requirements

RAINFALL-RUNOFF RELATIONSHIPS

The relationship between precipitation and runoff within a watershed or drainage area is a critical element for estimating the key metrics (peak flow discharge, runoff volume) needed to design and demonstrate compliance for stormwater management. The two key aspects of runoff generation (the fraction of rainfall available to produce surface runoff) include ***rainfall loss,*** which takes into consideration infiltration and depression storage, and ***runoff movement*** through a drainage area based on catchment characteristics such as topography, land cover, and land use. The extent to which different rainfall-runoff processes are incorporated into runoff estimation is dependent on the method used.

HYDROGRAPHS

A runoff hydrograph is a graphical plot of surface runoff (discharge from a watershed) with respect to time as a response to precipitation. Runoff occurring in a watershed flows downstream in various patterns that are influenced by several factors, such as the amount and distribution of the rainfall, rate of snowmelt, stream channel hydraulics, infiltration capacity of the watershed, and others, which are difficult to define.

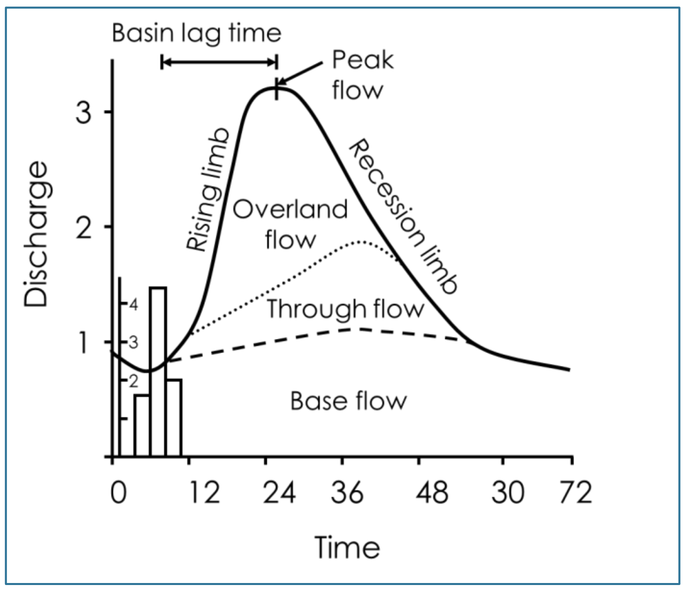


Figure 9-1: Hydrograph

The derivation of a hydrograph is the basis by which the watershed response to rainfall (in terms of runoff) can be predicted and evaluated. Alterations in the drainage basin, such as urbanization, may be reflected in the size and/or shape of the hydrograph. Modifications or design considerations aimed at minimizing these effects draw on the data supplied by the hydrograph.

Characteristics of all hydrographs as shown in the previous figure include:

1. Rising limb – Stage (elevation) and discharge are increasing with time.
2. Crest or Peak – The maximum stage and discharge for the measured or hypothetical storm event.
3. Receding limb – Stage and discharge are decreasing with time.
4. Base flow – Water emanating from the groundwater table into the stream.
5. Through flow – Water from rainfall that moves laterally through the soil then returns to the surface, as overland flow, prior to entering a stream.
6. Overland flow – Water from rainfall that flows over land surface, which contributes to direct runoff volume (typically includes through flow).
7. Interflow (not shown) – Water from rainfall that moves laterally through the soil before returning to overland flow, streams, or groundwater.

Stream response or stormwater facility discharge can be collected using water flow recording gauges and are often used in conjunction with rainfall recording gauges to present rainfall (depth or intensity) over time (also known as a hyetograph) simultaneously with the natural hydrograph for a specific storm event or period of time. The example hyetograph and hydrograph depicted below show the rainfall and stormwater facility discharge for a specific storm event in 2013.

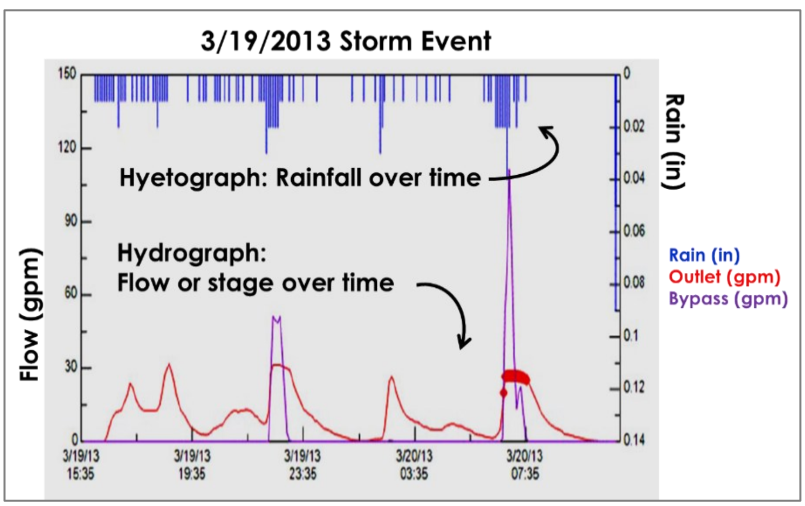


Figure 9-2: Hyetograph and Hydrograph for 2013 Storm Event

The hydrographs below show how differently a stream responds to a storm and stormwater runoff in a pre- and post- development watershed.

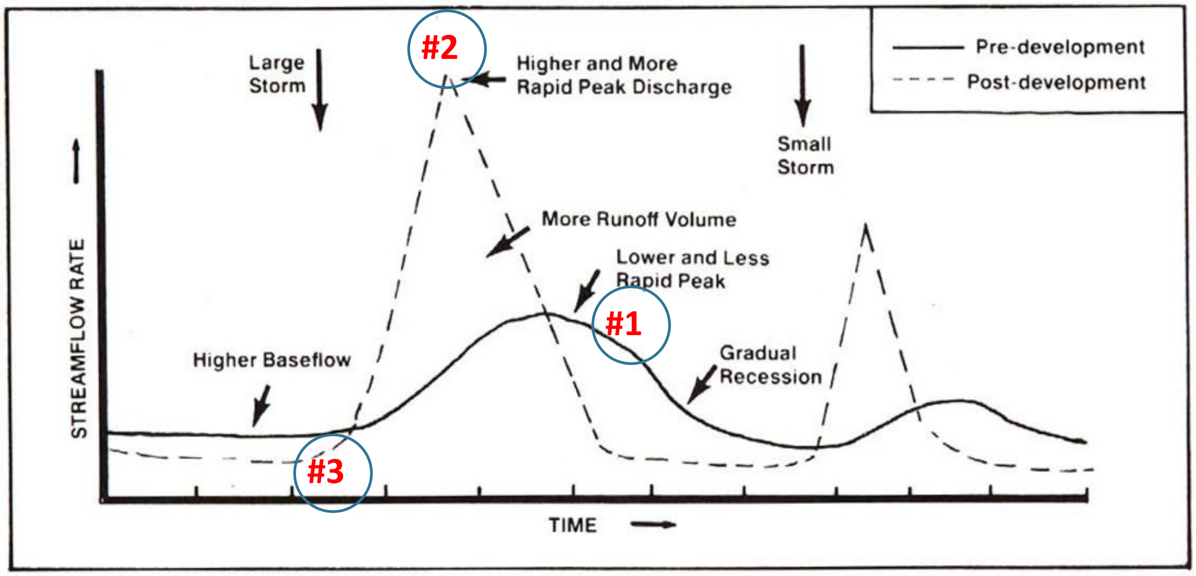


Figure 9-3: Pre- and Post-Development Stormwater Runoff Hydrographs

1. Following a storm in a ***pre-development*** watershed, the peak discharge, or flow that occurs when the maximum flood state, or depth, in a stream is reached, gradually increases, and gradually declines (curve is rounded).

2. After a storm in a ***post-development*** watershed**,** the peak discharge can be two to five times higher than in a pre-development watershed. This characterization translates into the sharp peak and increased size of the post-development hydrograph.

   This happens in a post-development watershed because there is more impervious surface and less opportunity for evapotranspiration and infiltration.

3. It takes less time for runoff to travel over the impervious surface in a ***post-development*** watershed, so it takes less time for runoff from the farthest reaches of the watershed to reach a stream (time of concentration). The energy of stream flows ranging from low to bankfull flows can most quickly alter a stream channel's physical shape and size.

The following hydrographs represent stream responses (discharges) at three different gauging stations in the Chickahominy River watershed. The data was normalized in this graphical representation to account for the different drainage area sizes at each of the stations. As presented, the relative hydrographs can be directly compared. The same patterns described above for the stream's response to stormwater runoff, are easily observed between the undisturbed forest watershed, the developed urban watershed, and the intermediate suburban watershed.

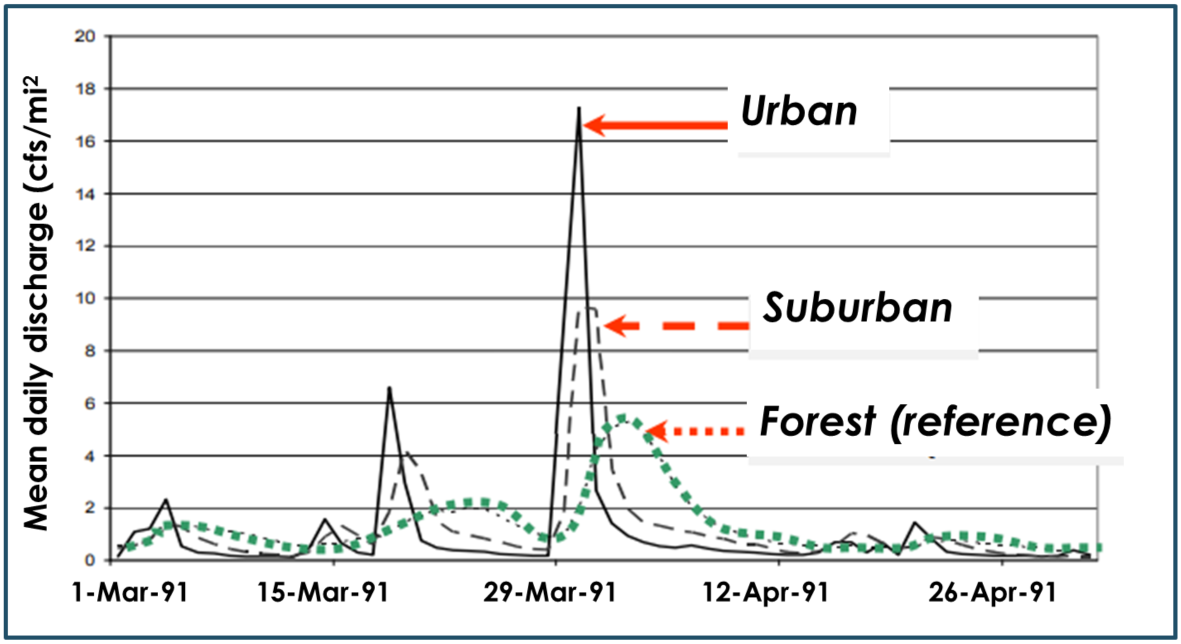
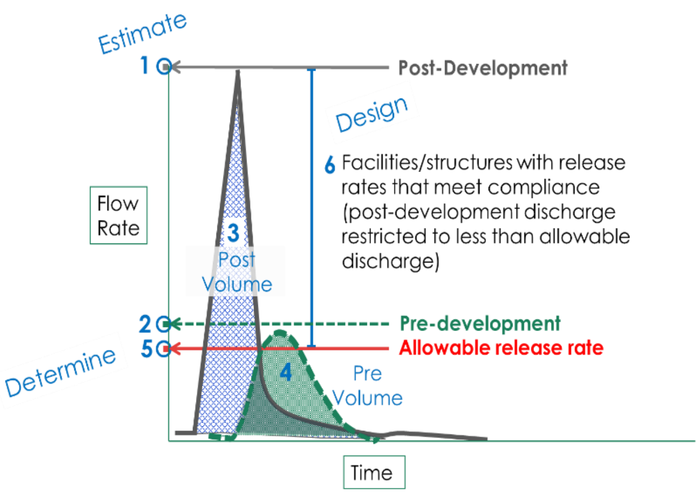


Figure 9-4: Normalized mean daily discharge for three gauging stations in the Chickahominy River watershed, Virginia from Facazia and Cooper, 1995 (Barten, 2013)

As seen above, natural hydrographs can be developed using extensive watershed gauge data. However, the lack of such extensive data for existing conditions and the requirement to forecast runoff conditions for proposed developed conditions necessitate estimation of rainfall-runoff relationships. These relationships are critical in that they can be used to generate runoff hydrographs, peak flow estimates, and runoff volumes that form the starting point for stormwater management.

MANAGING STORMWATER

The overall purpose of stormwater management is to control runoff to make better use of the resource and prevent damages due to flooding, erosion, sedimentation, and pollution. The general approach used by a designer to manage post-development stormwater on a site is illustrated in the graphic below:



Estimate

☐ **Use correct inputs and assumptions**

☐ 1. Post-development peak discharge rate

☐ 2. Pre-development peak discharge

☐ 3. Post-development volume

☐ 4. Pre-development volume

Determine

☐ **Use applicable requirement(s) with correct calculation(s)**

☐ 5. Allowable release rate

Design

☐ **Incorporate results of modeling and other facility/structure specific requirements into design**

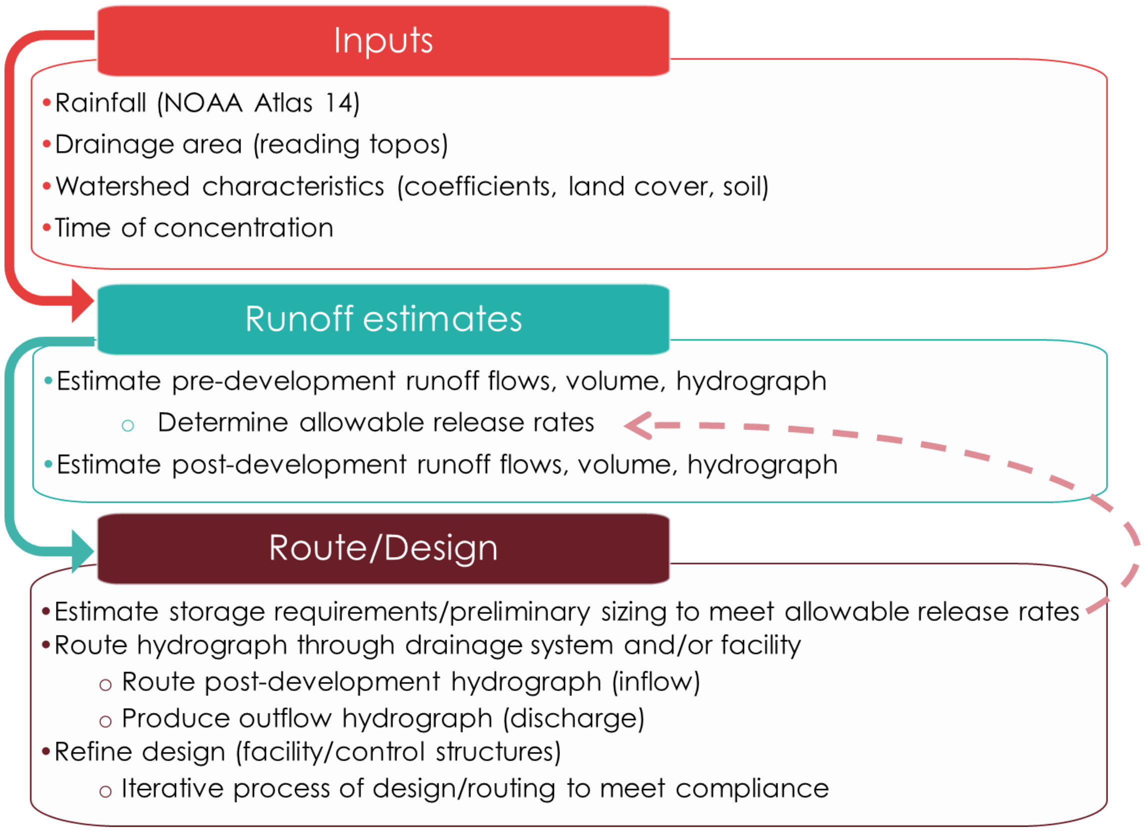
☐ 6. Facilities/structures with release rates that meet compliance (post-development discharge restricted to less than allowable discharge)

In other words, a designer must estimate:

- Peak discharge
  - To evaluate channel protection compliance
  - To evaluate flood protection compliance

- Runoff volume
  - To design stormwater management practices
    - Facility size
    - Discharge structure design
  - To evaluate channel protection compliance (when using energy balance)
  - To evaluate sheet flow
  - To design and evaluate runoff reduction alternatives

Approaching water quantity compliance for both designer and plan reviewer can start with the estimation of hydrograph metrics needed for the determination of compliance targets, all of which then serve as inputs for ultimate stormwater management design elements.



Many techniques of stormwater management are available to a designer, and the field is open for new innovative approaches. The general concepts are applicable to small or large watersheds. Generally, they consist of:

- Runoff storage:
  - Detention (short term storage designed to delay runoff and, thus, reduce flood peaks and runoff volume), requires less storage than retention since significant outflow occurs while facility (reservoir, etc.) is storing water.
  - Retention (store total runoff hydrograph and release flow at controlled rate over a long period), provides more positive control of runoff and may enable water to be used in more productive manners, such as water supply, hydropower, etc.
  - Many water resources projects are multi-purpose, which means that more than one function is served. For example, a reservoir could be used for both water supply and

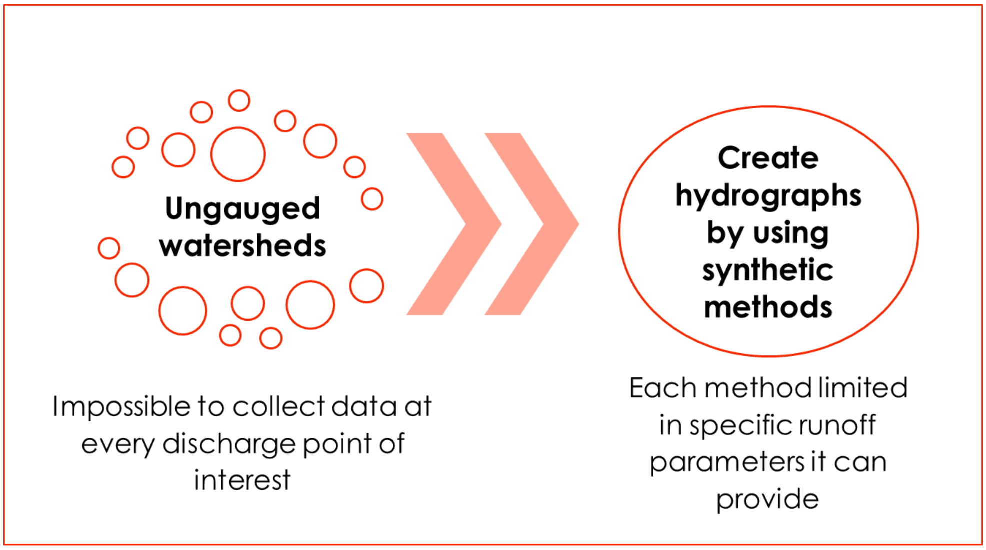
flood control. In this case, some of the runoff hydrograph from the storm would be stored for water supply (retention) and the remainder would be released at a controlled rate (detention)

- Runoff reduction, such as with infiltration
- Hydraulic management/improvements for the control of runoff and protection of drainage channels
- A combination of the above

Empirical methods have been developed to assist in estimating potentially complex hydrographs. The critical element of these methods, as with any hydrologic analysis, is the accurate description of the watershed's rainfall-runoff relationship.

9d. Estimating Runoff

As mentioned above, most watersheds or drainage areas are ungauged and hence synthetic methods are used to create hydrographs. There are various synthetic methods, a few of which will be covered in this module.



A synthetic hydrograph is a simulation of a natural hydrograph using watershed parameters and storm characteristics. The shape and characteristics of a runoff hydrograph for a given watershed are determined by the specific characteristics of the storm (rainfall duration, time-intensity patterns, area distribution of rainfall, and depth of rainfall) and the physical characteristics of the watershed (shape, slope, groundcover, etc.). Since the physical characteristics of a watershed are constant, the shape of hydrographs from storms of similar rainfalls is assumed to be similar.

This is the basis of the unit hydrograph, which is a commonly used synthetic hydrograph for modeling and design. The unit hydrograph is the hydrograph that results from one inch of precipitation excess generated uniformly over the watershed at a uniform rate during a specified time period. In essence, the runoff volume under the hydrograph is adjusted to equal one inch of equivalent depth over the watershed. Different modeling approaches for runoff estimation build on this concept of the unit hydrograph.

The practice of estimating runoff as a fixed percentage of rainfall has been used in the design of storm drainage systems for over 100 years. Despite its simplification of the complex rainfall -

runoff processes, it is still the most commonly used method for urban drainage calculations. It can be accurate when drainage areas are subdivided into homogeneous units, and when the designer has enough data and experience to use the appropriate factors.

For watersheds or drainage areas comprised primarily of pervious cover, such as open space, woods, lawns, or agricultural land uses, the rainfall/runoff analysis becomes much more complex. Soil conditions and types of vegetation are two of the variables that play a larger role in determining the amount of rainfall that becomes runoff. In addition, other types of flow have a larger effect on stream flow (and measured hydrograph) when the watershed is less urbanized. These are:

1. **Surface runoff** occurs only when the rainfall rate is greater than the infiltration rate and the total volume of rainfall exceeds the interception, infiltration, and surface detention capacity of the watershed. The runoff flows on the land surface collecting in the stream network.

2. **Subsurface flow** occurs when infiltrated rainfall meets an underground zone of low transmission and travels above the zone to the soil surface to appear as a seep or spring.

3. **Base flow** occurs when there is a fairly steady flow into a stream channel from natural storage. The flow comes from lakes, swamps, or an aquifer replenished by infiltrated rainfall or surface runoff.

In watershed hydrology, it is customary to deal separately with base flow and to combine all other types of flow into direct runoff. Depending upon the requirements of the study, the designer can calculate the ***peak flow rate***, in ***cfs*** (cubic feet per second), of the direct runoff from the watershed or determine the ***runoff hydrograph*** for the direct runoff from the watershed. A hydrograph shows the volume of runoff as the area beneath the curve and the time-variation of the discharge rate.

If the purpose of a hydrologic study is to measure the impact of various developments on the drainage network within a watershed or to design flood control structures, a hydrograph is needed. If the purpose of a study is to design a roadway culvert or other simple drainage improvement, only the peak rate of flow is needed. Therefore, the purpose of a given study will dictate the methodology that should be used. ***Procedures such as the Rational Method and TR-55 Graphical Peak Discharge Method do not generate a runoff hydrograph. The TR-55 Tabular Method and the Modified Rational Method do generate runoff hydrographs.***

The Rational Method, Modified Rational Method, and the TR-55 Graphical Method (and mention of the TR-55 Tabular Method) are briefly described in this module. Plan reviewers should be familiar with all of them since they require different types of input and generate different types of results.

Many software programs are available, that use these methodologies to predict the rainfall-runoff relationship described previously. Many of these programs also “route” the runoff hydrograph through a stormwater management facility, calculating the peak rate of discharge and a discharge hydrograph.

Readily available software programs utilize SCS Methods such as TR-55 and TR-20. The accuracy of the computer model is based upon the accuracy of the input that is typically generated through the Rational or SCS methodologies. The designer and plan reviewer should be familiar with all the methods covered here since any one may be appropriate for the specific site or watershed being modeled. Some examples of the different software programs available that use the different methodologies mentioned in this module are referenced in Appendix A of the VSWHB. Some of the most common of these are HydroCAD, Hydraflow, and PondPack.

All the methods presented in the participant guide make ***assumptions*** and have ***limitations on accuracy***. When these methods are used correctly, they can generally all provide a reasonable estimate of the peak rate of runoff from a drainage area or watershed.

Inputs

- Rainfall
- Drainage area (reading topos)
- Watershed characteristics (coefficients, land cover, soil)
- Time of concentration

An examination of the inputs used in hydrologic and hydraulic analyses is one of the most important functions that fall to the plan reviewer when reviewing plans for stormwater management compliance. The primary inputs include rainfall, drainage area boundaries, watershed parameters, and time of concentration. Each of these is briefly discussed in the following sections.

RAINFALL

Precipitation or rainfall characteristics used for the purposes of stormwater management compliance must adhere to the requirements laid out in VESM Regulation as described earlier in section 9b. Part V, Article 3 and Part V, Article 4 both require use of the 24-hour storm duration using the rainfall distribution recommended by the NRCS, except when using methods such as the Modified Rational Method that require the storm of critical duration. Both methods also require the use of design storms (1-year, 2-year, 10-year), depending on the applicable technical criteria. Part V, Article 3 specifically identifies NOAA Atlas 14 as the data server that must be used.

- 24-hr — Storm duration (units of time)
- ? inches — Storm depth (units of length)
- ? in/hr — Storm intensity (I) = depth(d) / time(t)
- 1-yr, 2-yr,10-yr — Frequency (recurrence interval)

Return Period (T) = 1/Probability (P)

100 year event = 1/100 or 0.01 or 1% chance of occurring in any given year

10 year event = 1/10 or 0.1 or 10% chance of occurring in any given year

Synthetic Rainfall Distributions and Rainfall Data Sources

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 originally 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. These rainfall distribution types were based on Technical Paper 40 rainfall data as discussed in the next section.

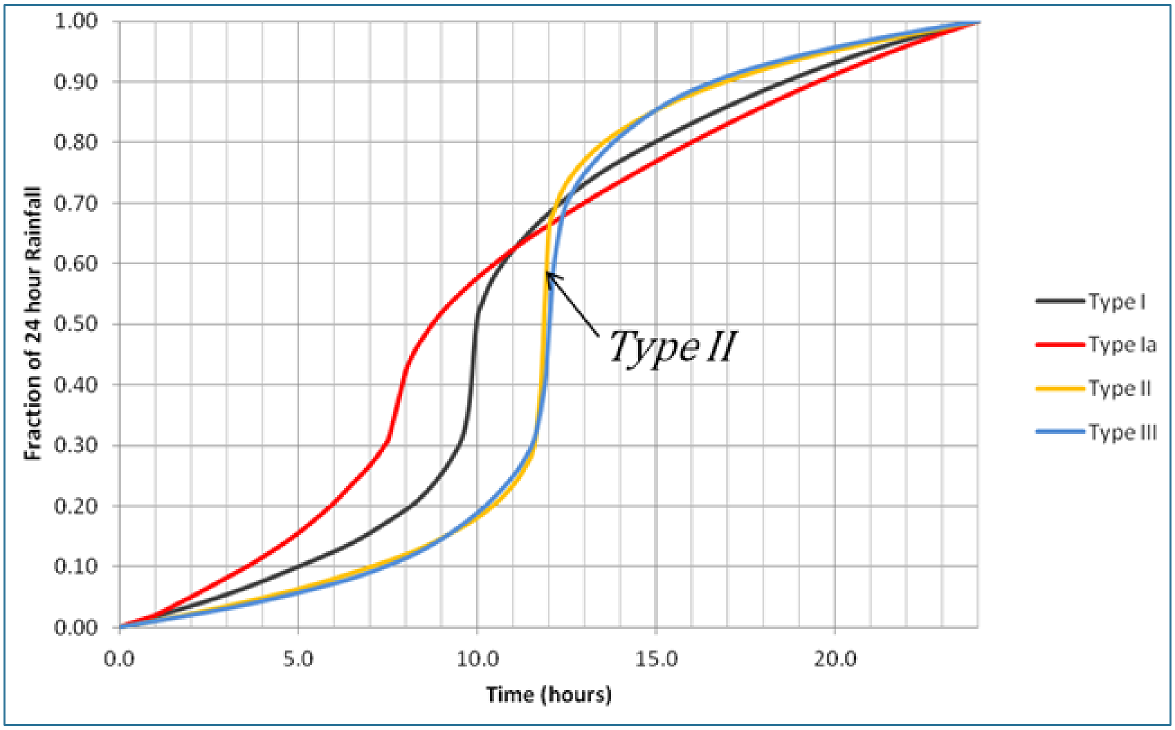


Figure 9-5: Precipitation-Distribution (TR-55, 1986)

Figure 9-6 below is reproduced from TR-55 and shows the appropriate type of rainfall distribution based upon geographic boundaries across the United States. Figure 9-7 includes a view of the boundaries specific to Virginia.

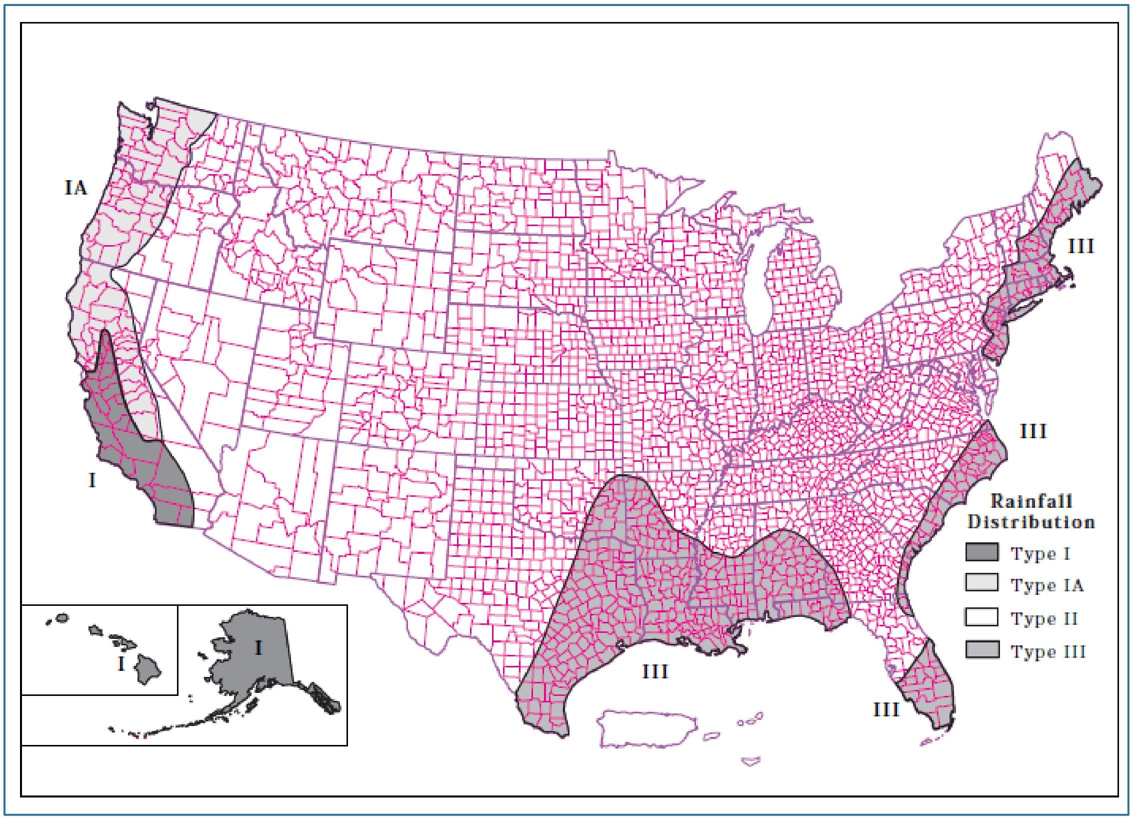


Figure 9-6: Approximate Geographic Boundaries for U.S. (TR-55, 1986)

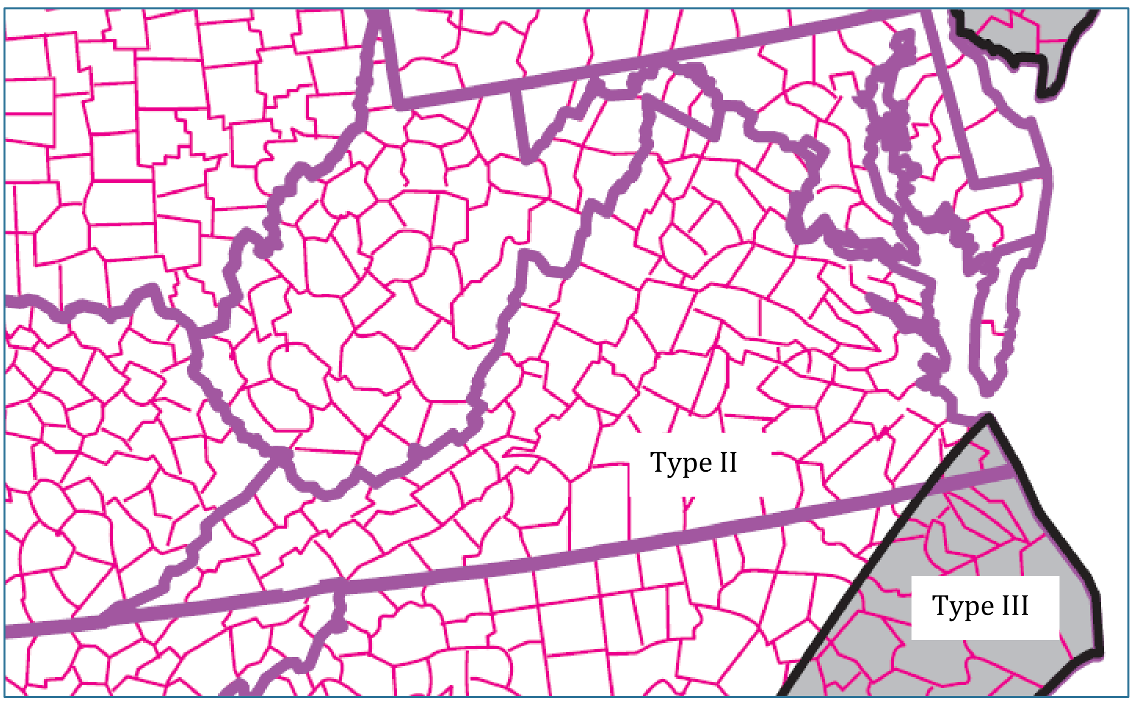


Figure 9-7: Approximate Geographic Boundaries for Virginia (TR-55, 1986)

Rainfall Data Sources

TECHNICAL PAPER 40 (TP40)

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 (TR-55, 1986).

TP-40 was based upon historic rainfall data collected through 1958. A substantial amount of rainfall data has been collected since TP-40 was published, so the National Oceanic and Atmospheric Administration (NOAA) published a new document that supersedes TP-40, titled **Atlas 14 Precipitation-Frequency Atlas of the Eastern United States**. NOAA used periods of record for rainfall stations up through December 2000 to compute precipitation-duration-frequency values. This additional 42 years of data gives different frequency-duration rainfall values than TP-40. These values were updated in 2004 and again in 2006 for Virginia and were incorporated into part 650 of the NEH in 2008 and again in 2012. The VESM Regulation require that designers use updated rainfall data based upon the NOAA Atlas 14 publication for stormwater management computations and modeling.

NOAA ATLAS 14

NRCS is replacing the use of its legacy rainfall distributions (Type I, Type IA, Type II, and Type III) with rainfall distributions based on NOAA Atlas 14 precipitation-frequency data. Regional Virginia rainfall distributions have been developed for use in the NOAA Engineering EFH-2 software program, WinTR-55, and WinTR-20. Rainfall data is accessible through an online Precipitation Frequency Data Server (PFDS): https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=va.

Five rainfall distribution types (NOAA A, NOAA B, NOAA C, NOAA D, and DMV C) were developed from the NOAA 14 data to replace the NRCS Type-II rainfall distributions. The new rainfall distribution types were developed for the NOAA Atlas 14 Volume 2 region that includes 13 states from New Jersey west to Illinois and southeast to South Carolina. See Figure 9-8 below.

> NOAA Atlas 14 data updates rainfall magnitude and distributions. NOAA Atlas 14 data does not fit the TP-40 storm distributions (Type I, Type II, Type III, etc.) for all return periods; therefore, each data location now has a unique rainfall distribution for each frequency (1-year to 500-year).

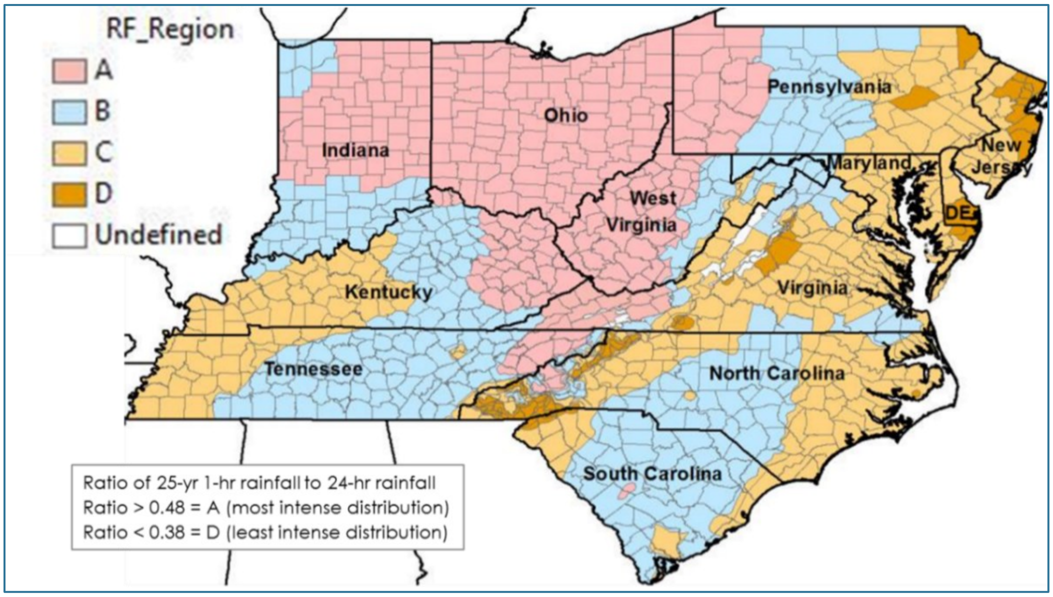


Figure 9-8: Regional rainfall distributions for the Ohio Valley and neighboring states (NRCS, 2015)

The NRCS Virginia office published revised 24-hour rainfall depths for Virginia Cities and Counties based upon the **NOAA Atlas 14** publication. Virginia rainfall data using NOAA Atlas 14 is included in a State Supplement to the National Engineering Field Handbook, Chapter 2 **<u>Estimating Runoff and Peak Discharges</u>** (210-VI-NEH, Part 650). The supplement includes updated tabulation of 24-hour rainfall totals for the 1-, 2-, 5-, 10-, 25-, 50-, and 100-year events.

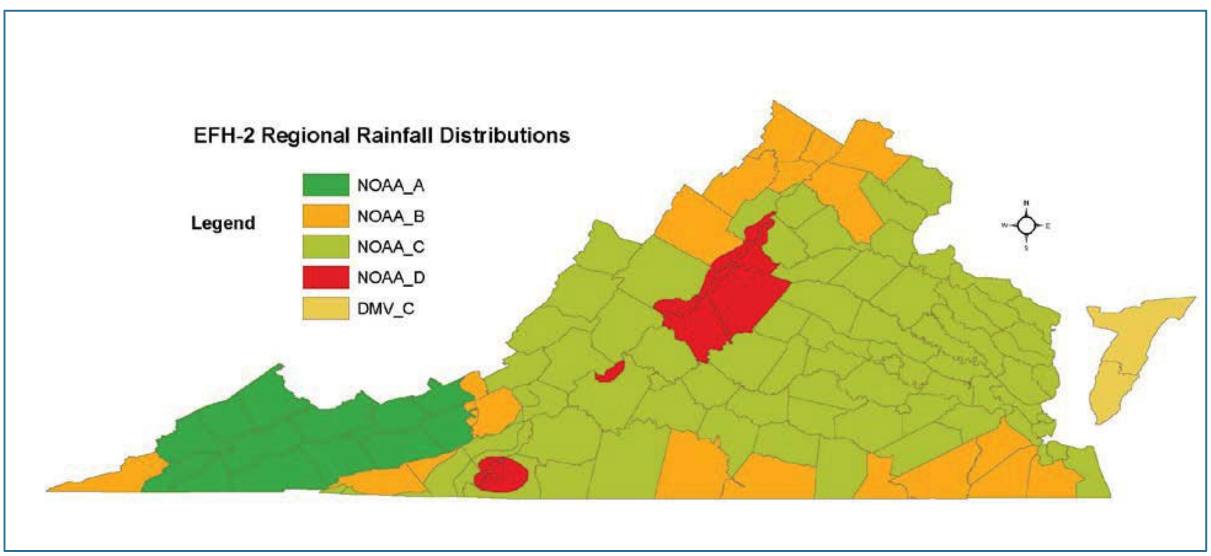


Figure 9-9: Rainfall Distribution Types for Virginia (210-VI-NEH, Amend. VA4, August 2012)

The boundaries of the four rainfall distribution regions (NOAA A-D) are based on the ratio of the 25-year (4% chance), 60-minute rainfall to the 25-year (4% chance), 24-hour rainfall. Areas with a ratio greater than 0.48 are assigned rainfall distribution A. This is the most intense rainfall distribution. Areas with a ratio between 0.43 and 0.48 are assigned rainfall distribution B. Areas with a ratio between 0.38 and 0.43 are assigned rainfall distribution C. Areas with a ratio less than 0.38 are assigned rainfall distribution D. This is the least intense rainfall distribution. The rainfall type (DMV C) was developed for the Eastern Shore, part of the Delmarva Peninsula, as the rainfall-runoff events on the Eastern Shore are better described separately. County division and large independent cities are the basis for selecting areas that represent rainfall magnitude and distribution zones.

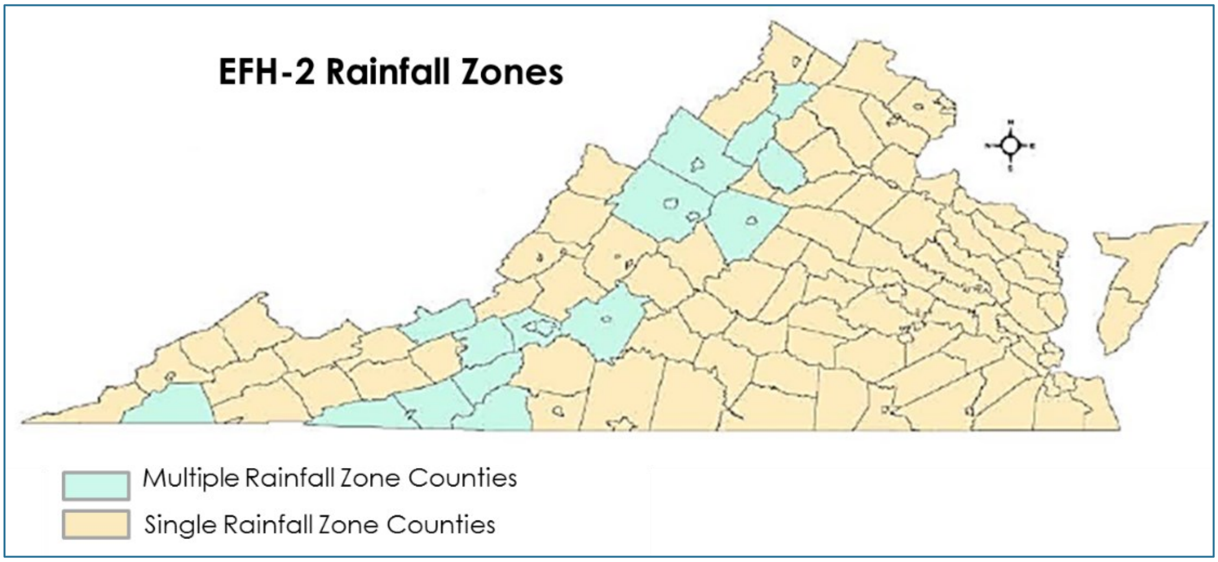


Figure 9-10: EFH-2 Rainfall Zones ([210-VI-NEH, Amend. VA4, August 2012])

It should be noted, the updated rainfall data can be highly variable even on a county basis, particularly in the mountainous regions where orographic effects are present. 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 (210-VI-NEH, Amend. VA4, August 2012) includes maps showing the breakdown of rainfall within localities with significantly different rainfall totals reported.

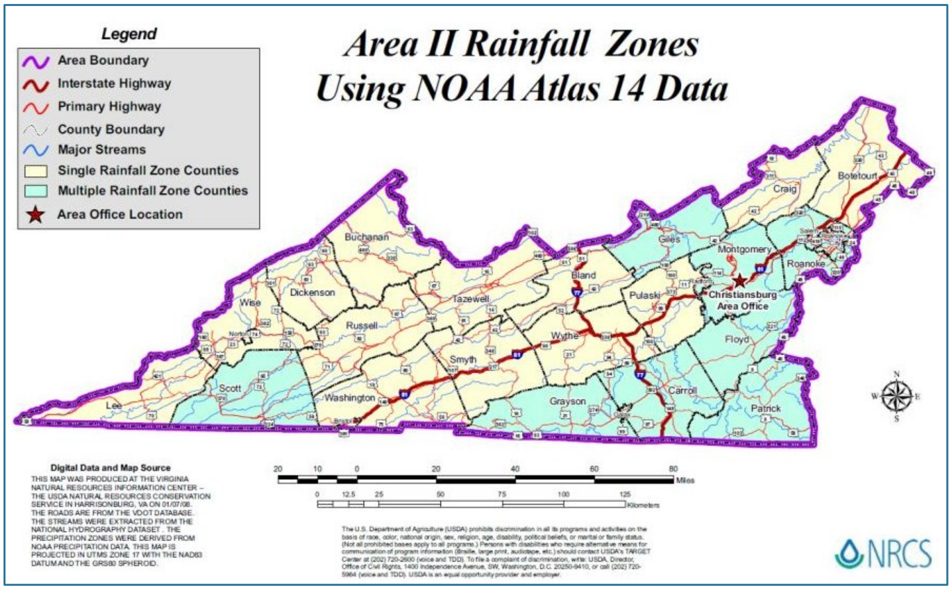


Figure 9-11: Area II Rainfall Zones Using NOAA Atlas 14 Data ([210-VI-NEH, Amend. VA4, August 2012](#))

Using one rainfall magnitude and distribution for an entire division (county or city) that contains a mountain region can result in an unacceptable error (> 10%) in rainfall magnitude and distribution for any one particular area within a county. For example, the Rockingham County 100-year 24-hour storm ranges from 6.07 inches to 10.48 inches.

The following plots are for use with 24-hour design storms. They represent the accumulated rainfall during the 24-hour storm duration on a non-dimensional basis. The maximum accumulated rainfall in the plot is 1.0, which represents the total storm 24-hour rainfall. These rainfall distributions are represented in WinTR-20 in tabular format at a time interval of 0.1-hour.

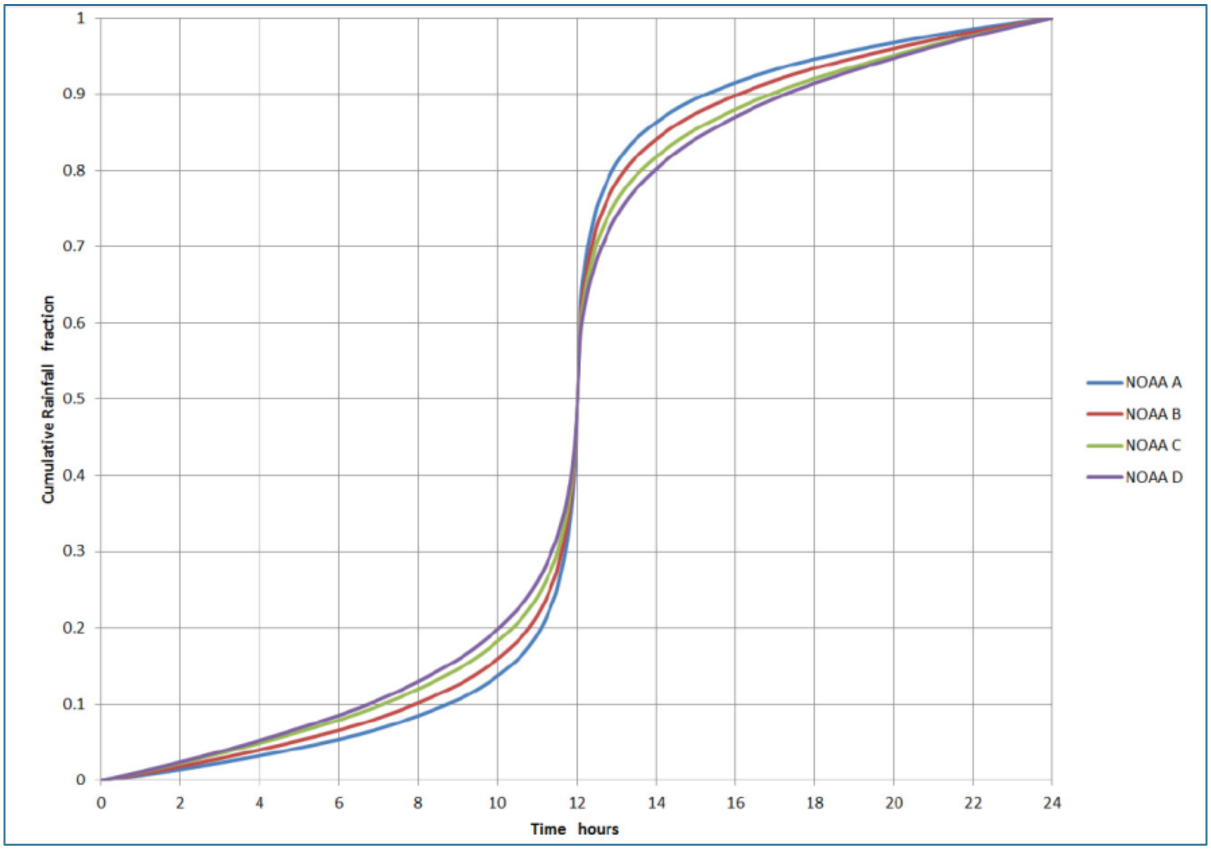


Figure 9-12: Plots of the Ohio Valley and neighboring states' rainfall distributions ([210-VI-NEH, Amend. VA4, August 2012](#))

Precipitation depth can be found using NOAA Atlas 14 at:
https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html

An example of how to use NOAA Atlas 14 is included below:

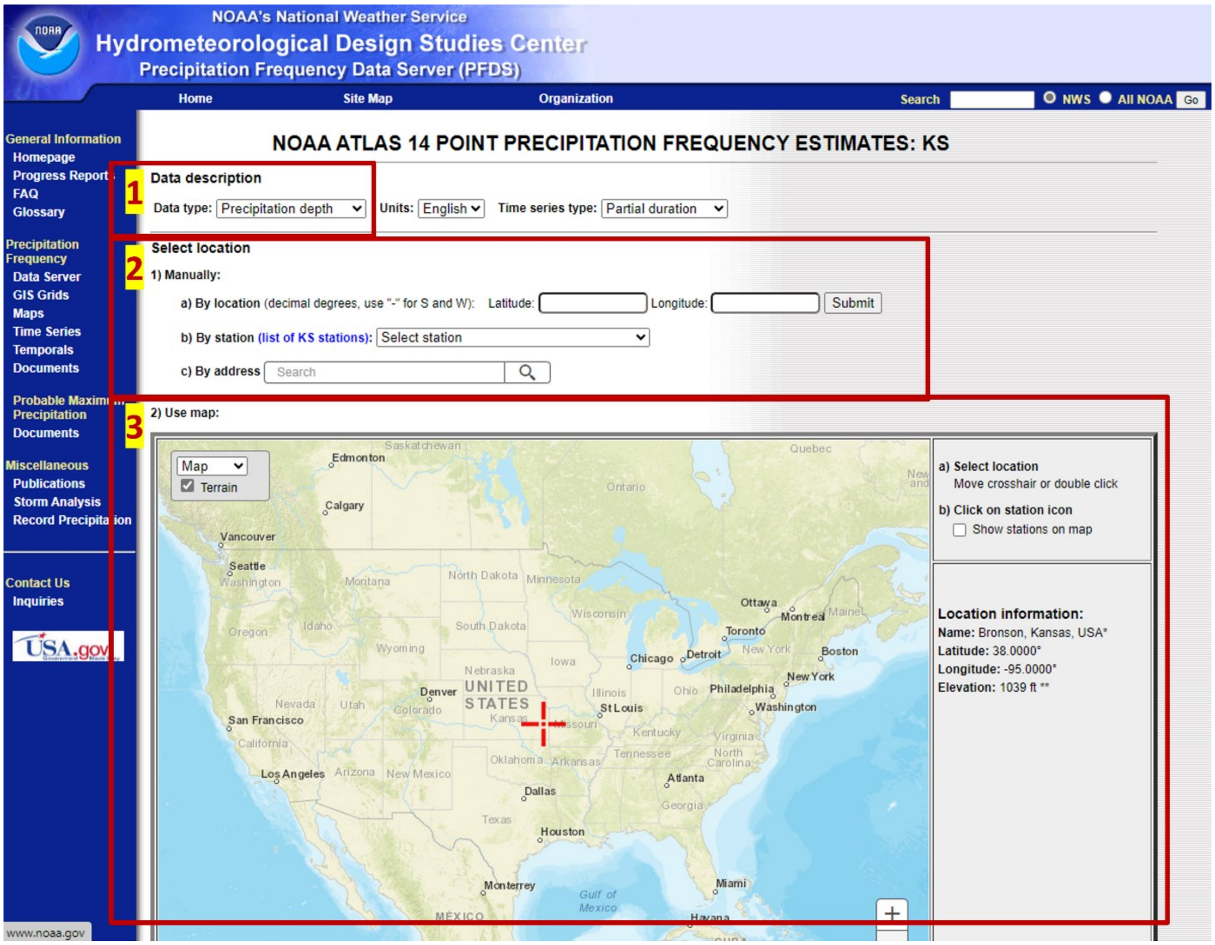


Figure 9-13: NOAA Atlas 14 Homepage

When utilizing the NOAA Atlas 14 website to obtain or check precipitation data, the NOAA Atlas 14 homepage (Figure 9-13) presents the default data type as precipitation depth (1). It also includes four choices for identifying the site area of interest. Three location options are grouped together (2) and can be selected manually either by: (a) latitude and longitude, (b) station, or (c) site address. The fourth location option (3) is the ability to select a specific point on the provided map of the United States.

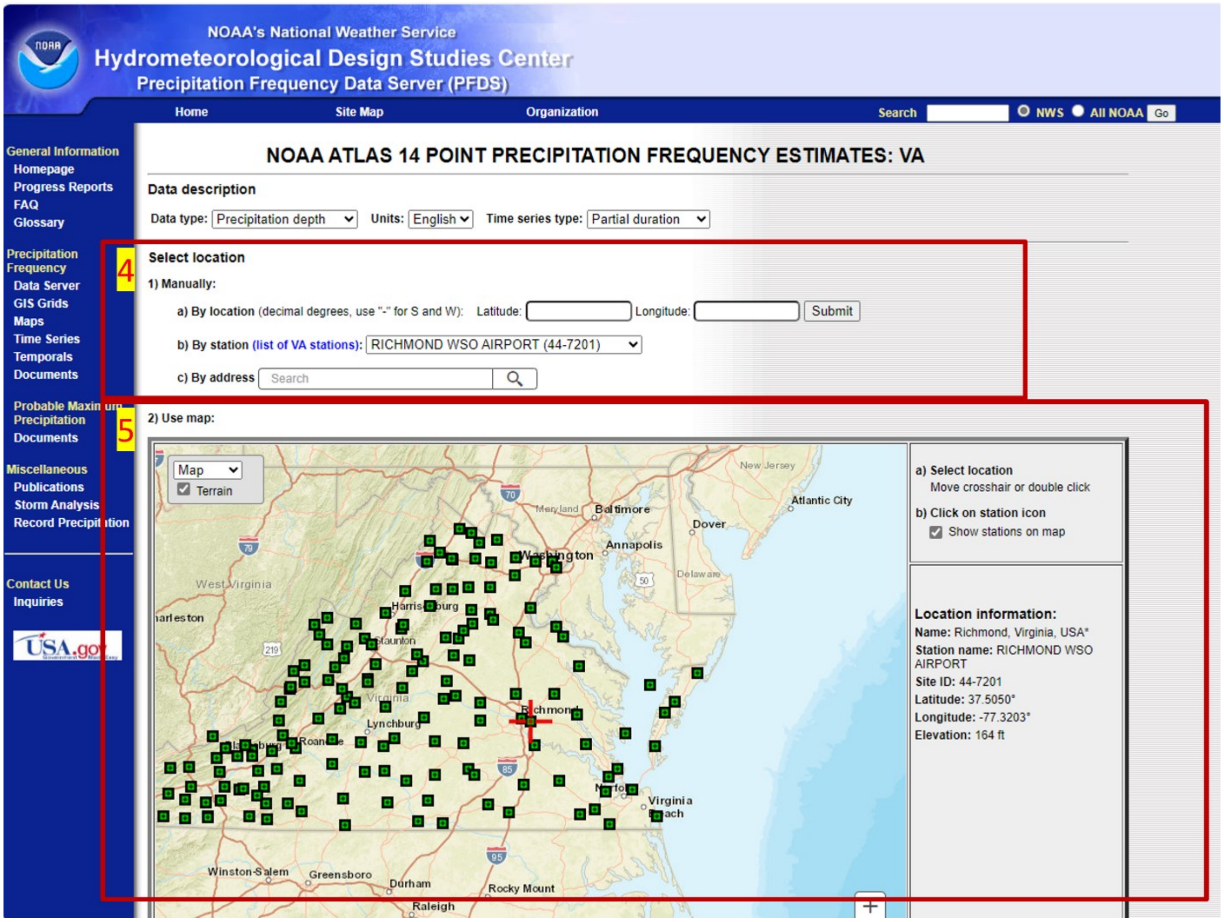


Figure 9-14: NOAA Atlas 14 Stations

Figure 9-14 shows an example of obtaining accurate precipitation depth data by selecting a location (4) using the station option (b). The map view of available stations in Virginia (5) is also shown. However, for the most accurate representation of site conditions, a designer and/or plan reviewer should use either the latitude and longitude (4a) or the site address (4c).

POINT PRECIPITATION FREQUENCY (PF) ESTIMATES

WITH 90% CONFIDENCE INTERVALS AND SUPPLEMENTARY INFORMATION
NOAA Atlas 14, Volume 2, Version 3

PF tabular | PF graphical | Supplementary information | Print page

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.376 (0.342-0.413)	0.446 (0.407-0.490)	0.522 (0.476-0.574)	0.585 (0.531-0.643)	0.657 (0.594-0.719)	0.711 (0.641-0.779)	0.762 (0.683-0.835)	0.808 (0.720-0.885)	0.863 (0.763-0.947)	0.906 (0.795-0.996)
10-min	0.600 (0.547-0.659)	0.713 (0.651-0.784)	0.837 (0.763-0.919)	0.936 (0.850-1.03)	1.05 (0.946-1.15)	1.13 (1.02-1.24)	1.21 (1.08-1.33)	1.28 (1.14-1.40)	1.36 (1.21-1.50)	1.43 (1.25-1.57)
15-min	0.751 (0.683-0.824)	0.896 (0.818-0.985)	1.06 (0.965-1.16)	1.18 (1.08-1.30)	1.33 (1.20-1.45)	1.43 (1.29-1.57)	1.53 (1.37-1.68)	1.62 (1.44-1.77)	1.72 (1.52-1.88)	1.79 (1.57-1.97)
30-min	1.03 (0.937-1.13)	1.24 (1.13-1.36)	1.50 (1.37-1.65)	1.72 (1.56-1.88)	1.96 (1.78-2.15)	2.16 (1.95-2.36)	2.34 (2.10-2.57)	2.52 (2.24-2.75)	2.73 (2.42-3.00)	2.90 (2.54-3.19)
60-min	1.28 (1.17-1.41)	1.55 (1.42-1.71)	1.93 (1.76-2.12)	2.23 (2.03-2.45)	2.62 (2.37-2.87)	2.92 (2.64-3.20)	3.23 (2.89-3.54)	3.53 (3.15-3.86)	3.92 (3.47-4.30)	4.24 (3.72-4.65)
2-hr	1.53 (1.39-1.69)	1.85 (1.69-2.05)	2.32 (2.11-2.56)	2.72 (2.46-3.00)	3.24 (2.92-3.56)	3.67 (3.28-4.03)	4.11 (3.65-4.51)	4.57 (4.03-5.00)	5.19 (4.52-5.68)	5.68 (4.91-6.23)
3-hr	1.65 (1.49-1.84)	2.00 (1.81-2.22)	2.51 (2.27-2.78)	2.94 (2.65-3.25)	3.51 (3.15-3.87)	3.98 (3.55-4.39)	4.48 (3.96-4.92)	4.97 (4.36-5.46)	5.66 (4.91-6.22)	6.22 (5.35-6.83)
6-hr	2.00 (1.80-2.24)	2.41 (2.17-2.69)	3.02 (2.71-3.37)	3.56 (3.18-3.96)	4.29 (3.81-4.76)	4.91 (4.33-5.44)	5.57 (4.88-6.17)	6.26 (5.44-6.93)	7.25 (6.22-8.01)	8.08 (6.85-8.93)
12-hr	2.38 (2.15-2.68)	2.87 (2.59-3.23)	3.62 (3.26-4.06)	4.30 (3.85-4.81)	5.25 (4.65-5.86)	6.08 (5.33-6.77)	6.98 (6.06-7.73)	7.95 (6.81-8.79)	9.36 (7.89-10.4)	10.6 (8.80-11.7)
6 24-hr	2.74 (2.51-3.01)	3.32 (3.05-3.65)	4.25 (3.89-4.68)	5.04 (4.60-5.54)	6.22 (5.64-6.82)	7.23 (6.51-7.91)	8.35 (7.46-9.12)	9.58 (8.48-10.4)	11.4 (9.96-12.4)	13.0 (11.2-14.1)
2-day	[illegible] (2.93-3.50)	[illegible] (3.55-4.24)	[illegible] (4.51-5.40)	[illegible] (5.31-6.37)	[illegible] (6.44-7.78)	[illegible] (7.38-8.97)	[illegible] (8.39-10.3)	[illegible] (9.47-11.7)	[illegible] (11.0-13.7)	[illegible] (12.2-15.5)
3-day	3.38 (3.10-3.70)	4.09 (3.76-4.48)	5.21 (4.78-5.70)	6.14 (5.62-6.71)	7.49 (6.81-8.18)	8.63 (7.80-9.42)	9.87 (8.85-10.8)	11.2 (9.97-12.2)	13.2 (11.6-14.4)	14.8 (12.9-16.2)
4-day	3.56 (3.28-3.89)	4.32 (3.97-4.72)	5.49 (5.05-6.00)	6.46 (5.93-7.05)	7.87 (7.18-8.59)	9.06 (8.21-9.88)	10.3 (9.32-11.3)	11.7 (10.5-12.8)	13.8 (12.2-15.0)	15.5 (13.5-16.9)
7-day	4.11 (3.79-4.48)	4.94 (4.55-5.39)	6.19 (5.70-6.74)	7.22 (6.64-7.86)	8.70 (7.97-9.47)	9.94 (9.05-10.8)	11.3 (10.2-12.3)	12.7 (11.4-13.9)	14.8 (13.1-16.1)	16.5 (14.5-18.0)
10-day	4.68 (4.33-5.07)	5.61 (5.19-6.08)	6.94 (6.42-7.51)	8.02 (7.41-8.69)	9.56 (8.79-10.3)	10.8 (9.90-11.7)	12.1 (11.0-13.2)	13.5 (12.2-14.7)	15.5 (13.9-16.9)	17.1 (15.2-18.7)
20-day	6.29 (5.85-6.77)	7.50 (6.98-8.07)	9.06 (8.42-9.76)	10.3 (9.56-11.1)	12.0 (11.1-12.9)	13.3 (12.3-14.4)	14.7 (13.5-15.8)	16.1 (14.7-17.3)	18.0 (16.3-19.4)	19.5 (17.5-21.1)
30-day	7.82 (7.32-8.35)	9.27 (8.68-9.89)	11.0 (10.3-11.7)	12.3 (11.5-13.1)	14.0 (13.1-15.0)	15.3 (14.3-16.4)	16.7 (15.4-17.8)	18.0 (16.6-19.2)	19.7 (18.1-21.0)	20.9 (19.1-22.5)
45-day	9.84 (9.24-10.5)	11.6 (10.9-12.4)	13.6 (12.8-14.4)	15.1 (14.1-16.0)	17.0 (15.9-18.1)	18.4 (17.2-19.6)	19.8 (18.5-21.1)	21.2 (19.7-22.5)	22.9 (21.2-24.4)	24.2 (22.3-25.8)
60-day	11.7 (11.0-12.4)	13.7 (12.9-14.5)	15.9 (15.0-16.8)	17.5 (16.5-18.5)	19.5 (18.4-20.6)	21.0 (19.8-22.2)	22.5 (21.1-23.8)	23.9 (22.3-25.3)	25.6 (23.9-27.2)	26.8 (24.9-28.5)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Estimates from the table in CSV format: Precipitation frequency estimates | Submit

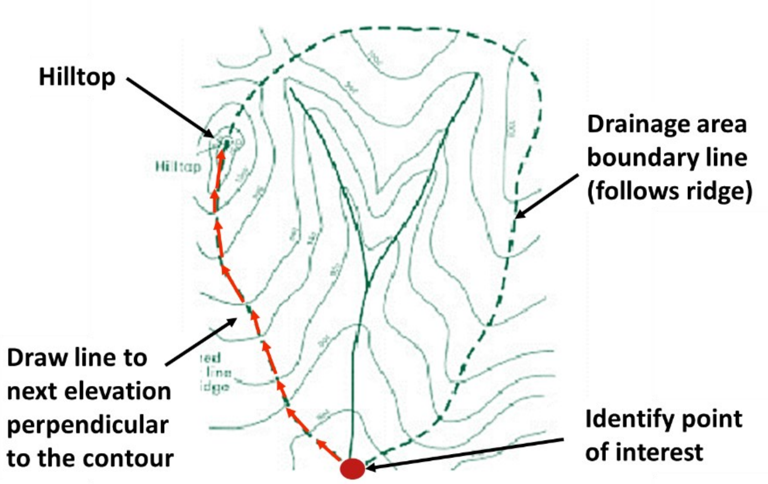
Main Link Categories:
Home | OWP

Figure 9-15: NOAA Atlas 14 Tabular Rainfall Depth

Be aware that NOAA Atlas 14 defaults to showing rainfall depth data in tabular format (Figure 9-15). For compliance with VESMA and the VESM Regulation, the 24-hour storm event (6) should be used for the recurrence interval design storm event (1-, 2-, and 10- year) highlighted above.

DRAINAGE AREA DELINEATION

A drainage area, also referred to as a watershed, is a land boundary in which surface water flows toward a single known point based on topography. Topographic maps and field surveys both serve as useful tools in the determination of a drainage area. Pre- and post-development drainage areas must be delineated accurately in order to develop effective stormwater management. Large drainage areas might require division into sub-drainage areas to account for major land use changes, obtain analysis results at different points within the drainage area, combine hydrographs from different sub-basins as applicable, and/or route flow to points of interest. Additionally, the local watershed (as defined by the 12-digit hydrologic unit code, HUC) within which a site is located must be identified (for each discharge point and receiving stream).



Drainage Area Delineation:

- Identify point of interest
- Delineate drainage divide
  - Drainage area boundary follows ridge line (perpendicular lines across contour lines representing highest elevations between two drainage areas to point of interest)

Note - A drainage divide always runs perpendicular to contour lines

Figure 9-16: Drainage Area Boundary

Watershed Characteristics (Rainfall-Runoff Coefficients)

For all runoff estimation methods, designers and plan reviewers need a good understanding of the physical characteristics of the watershed. Topographic maps can provide information for some features, such as topography and channel geometry. 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, groundcover, etc.

Every method to estimate runoff uses a coefficient that converts rainfall to runoff given certain watershed characteristics. A rainfall-runoff coefficient can be thought of as the hydrologic response of a watershed to rainfall. Various watershed characteristics, such as slope, land cover type, and soil type, are aggregated into a single value to represent the integrated effects of these drainage basin parameters. Individual map or geographic information system (GIS) layers can be used to facilitate an analysis of the site through what is known as map overlay, or a composite analysis. Each layer (or group of related information layers) is placed on the map in such a way as to draw a comparison and contrast with other layers. A composite layer is often developed to show all the layers at the same time. This composite layer can be a useful tool for documenting the watershed characteristics required to achieve a composite rainfall-runoff coefficient (topography, vegetation, soils, and land use).

Rainfall-Runoff Coefficients

- Estimate of watershed response to rainfall event
- Includes watershed characteristics: slope, cover, soil type
- C value (Rational), Rv (VRRM), CN (TR-55)
    - All take into account land cover types
    - Only CN and Rv account for soil types

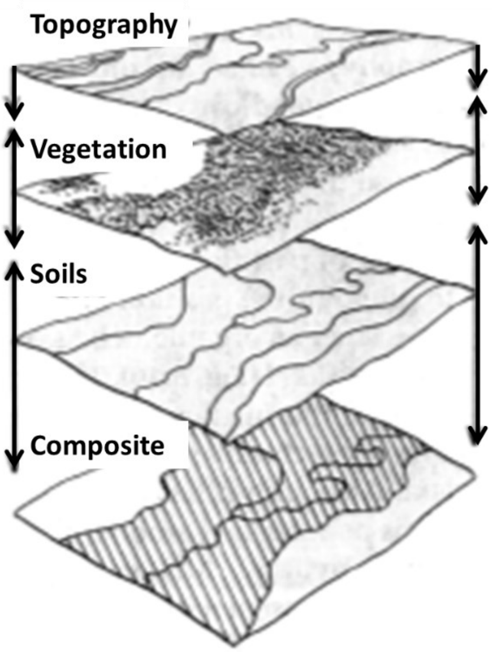


Figure 9-17: Composite Analysis (Marsh, 1983 from GSMM, 2016)

The coefficients used for the Rational and Modified Rational Method (C-value), TR-55 (Curve Number, CN), and the VRRM (Runoff Coefficient, Rv) will be discussed individually in the following sections of this Module and in Module 10.

TIME OF CONCENTRATION

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 hydraulically most distant point is the point with the longest travel time to the watershed outlet, not necessarily the point with the longest flow distance to the outlet. Time of concentration is generally only applied to surface runoff and may be computed using many different methods.

The time of concentration plays an important role in developing the peak discharge for a watershed, whether by rational, NRCS, or other runoff estimation methods. Urbanization usually decreases the T_c, which results in an increase in peak discharge. Any conditions that may act to decrease the flow time, such as channelization and channel improvements, must be taken into consideration to accurately model a watershed or drainage area. Conditions that may lengthen the flow time, such as surface ponding above undersized conveyance systems and culverts, must also be considered.

Time of concentration will vary depending upon slope and character of the watershed and the flow path. In hydrograph analysis, time of concentration is the time from the end of excess rainfall to the point on the falling limb of the dimensionless unit hydrograph (point of inflection) where the recession curve begins.

In cases where only a peak discharge and/or hydrograph are desired at the watershed outlet and watershed characteristics are fairly homogenous, the watershed may be treated as a single area. A time of concentration for that single area is required. A hydrograph is then developed (see the NRCS National Engineering Handbook, NEH630.16 for description of methods). However, if land use, hydrologic soil group, slope, or other watershed characteristics are not homogeneous throughout the watershed, the approach is to divide the watershed into several smaller subareas, which requires a time of concentration estimation for each subarea. Hydrographs are then developed for each subarea and routed appropriately to a point of reference using routing methods (see NEH630.17 for a description of flood routing methods).

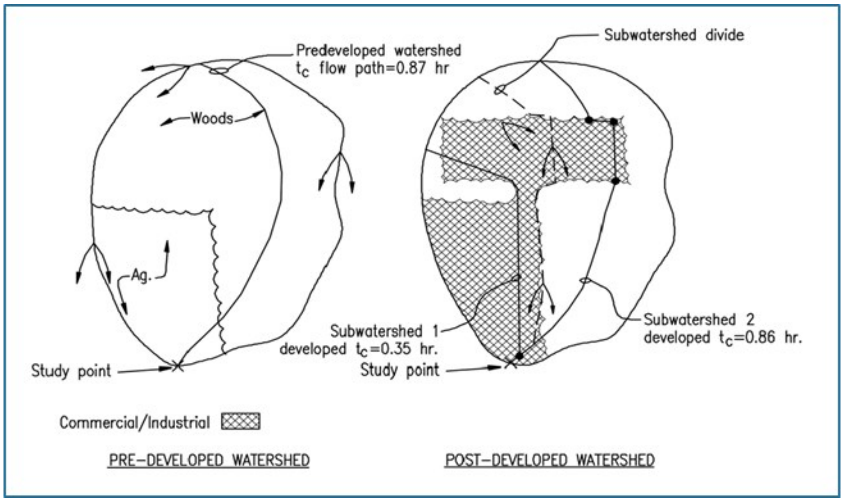


Figure 9-18: Time of Concentration (VSWHB)

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. Designers and plan reviewers 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 NRCS method is typically 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.

The three most common methods of determining time of concentration are described in the following pages. Two of the primary methods of computing time of concentration were developed by NRCS: the watershed lag method and the velocity method.

Watershed Lag Method

Watershed Lag Method

(See NEH Chapter 15, 2010)

$$L = \frac{l^{0.8}(S+1)^{0.7}}{1{,}900Y^{0.5}}$$

$$substitute\ L = 0.6T_c: \qquad T_c = \frac{l^{0.8}(S+1)^{0.7}}{1{,}140Y^{0.5}}$$

L = lag, hours
T_c = time of concentration, hours
l = flow length, ft
Y = average watershed land slope, %
S = maximum potential retention, in
$= \frac{1{,}000}{CN} - 10$

In the watershed lag method, which is the TR-20 default method, flow length is defined as the longest path along which water flows from the watershed divide to the outlet. Flow length can be measured using aerial photographs, quadrangle sheets, or GIS techniques.

Kirpich Method

The Kirpich Method is generally acceptable for natural basins that are dominated by channel flow of up to 200 acres. An adjustment factor can be used to correct for paved channels. It is similar to the Lag Method but will give shorter times.

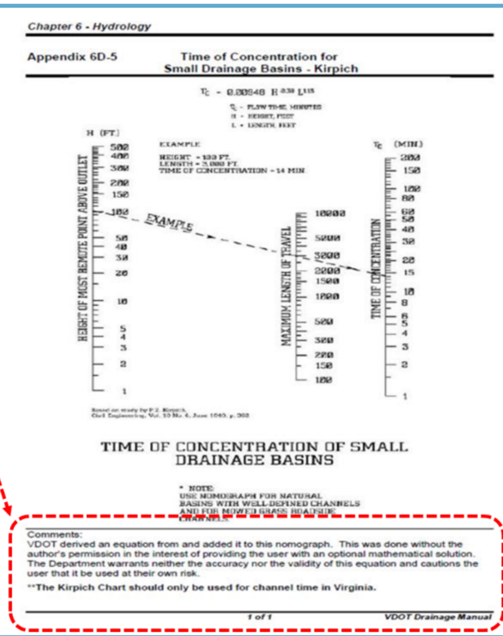
Kirpich Method

(VDOT Drainage Manual)

Comments:

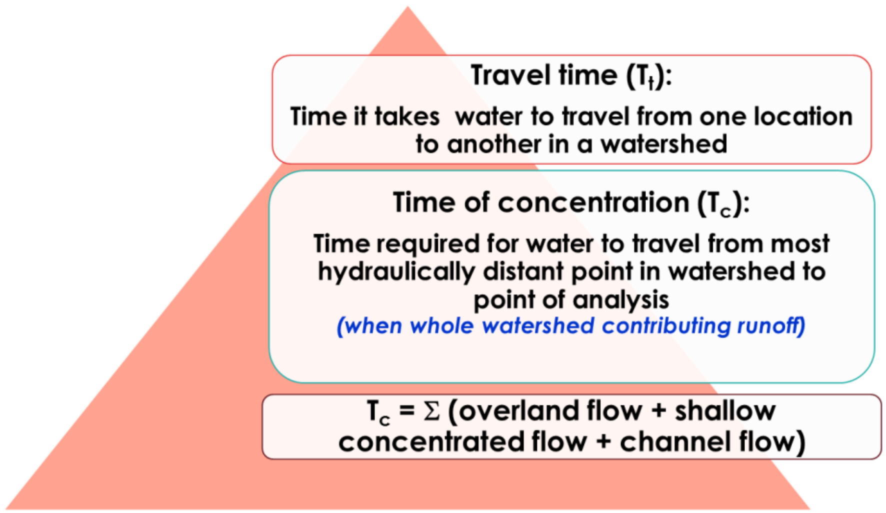
- VDOT derived equation added to nomograph.
- Done without author's permission to provide optional mathematical solution
- Dept does not warrant accuracy or validity of equation and cautions users to use at own risk.

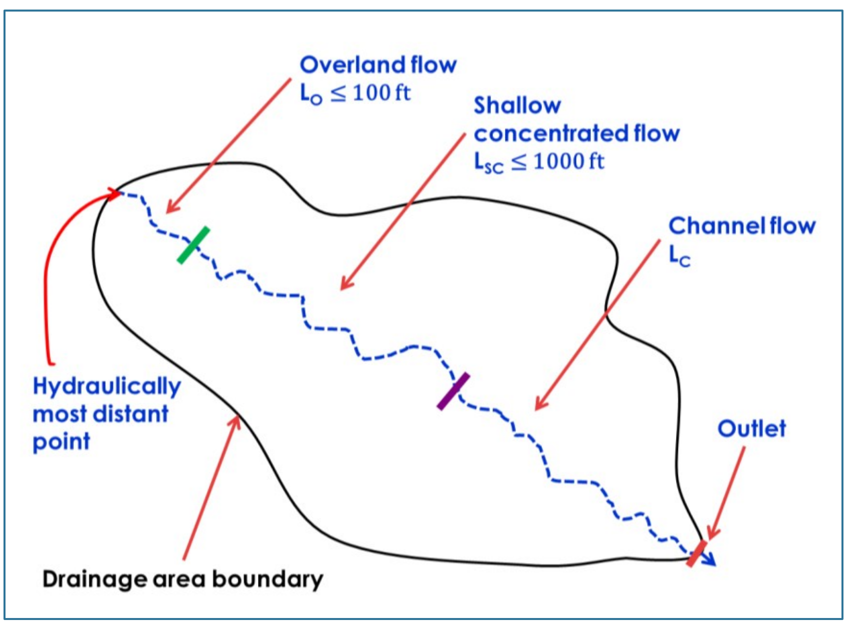
****Kirpich Chart should only be used for channel time in Virginia.**



NRCS TR-55 Time of Concentration Method (Velocity Method)

The NRCS T_c Velocity Method requires determination of a representative time of concentration flow path. This flow path is then broken down into the component flow types (overland flow, shallow concentrated flow, and channel flow). These flow types are influenced by surface roughness, channel shape, flow patterns, and slope and are discussed in the following section. The travel times for these consecutive components of runoff flow is then summed for the time of concentration representing the watershed or drainage area.





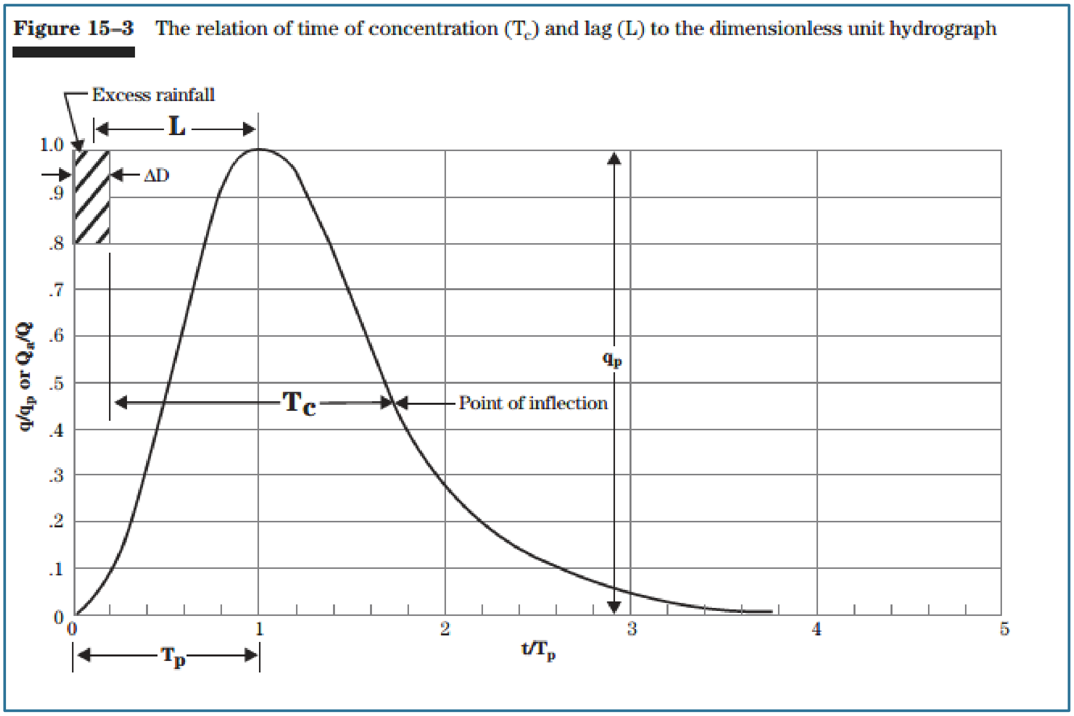
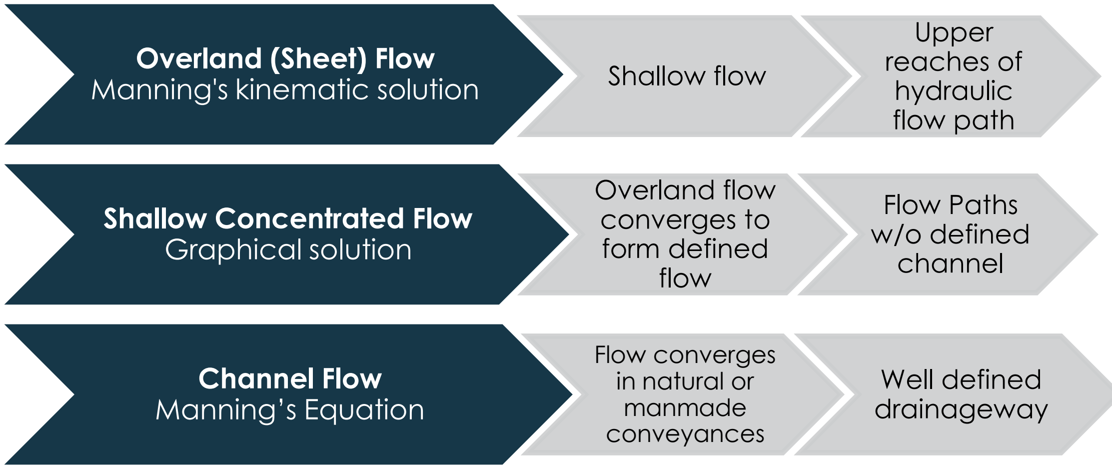


Figure 9-19: Dimensionless Unit Hydrograph (TR-55, 1986)

An important consideration when using this method is that the T_c flow path should not only represent the most hydrologically remote flow path but should also consider the relative homogeneity of the watershed. When a single T_c flow path does not represent the majority of the drainage area under consideration, either of the other methods should be referenced or the drainage area should be subdivided and examined individually with separate T_c values in developing a composite runoff estimate.

Flow Segments



Overland (Sheet) Flow

Overland 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 (at or near the drainage divides). 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.

- The flow depth is most likely below 0.05 feet and most certainly not greater than 0.1 feet (WinTR-55, 2009).
- A maximum length for sheet flow of 100 feet is stipulated in two technical guidance documents issued by the USDA NRCS: Small Watershed Hydrology, WinTR-55 User Guide (January 2009) and the National Engineering Handbook (NEH, 2010). This represents a reduction from the 300 feet of sheet flow distance used previously and much better represents the typical maximum distance before the combination of quantity and velocity create shallow concentrated flow.

TR-55 and the Virginia Stormwater Management Handbook (VSWHB) are both referenced in Part V, Article 3 of the VESM Regulation. It should be noted that the 1986 TR-55 guidance has been superseded by WinTR-55 as technical guidance.

Another approach (McCuen-Spiess limitation criterion, see Table 9-1) estimates a limiting length for overland flow based on various cover types in terms of Manning's n coefficient—slope combinations (NEH, 2010; VSWHB Section 5.3.2.2):

Table 9-1: Maximum sheet flow lengths using McCuen-Spiess limitation criterion (NEH, 2010)

Table 15–2 Maximum sheet flow lengths using the McCuen-Spiess limitation criterion

Cover type	*n* values	Slope (ft/ft)	Length (ft)
Range	0.13	0.01	77
Grass	0.41	0.01	24
Woods	0.80	0.01	12.5
Range	0.13	0.05	172
Grass	0.41	0.05	55
Woods	0.80	0.05	28

McCuen-Spiess limitation criterion:

$$l = \frac{100\sqrt{S}}{n}$$

l = limiting length of overland flow (feet)
n = Manning's roughness coefficient
S = slope (foot/foot)

Three methods for determining overland or sheet flow are presented here: (1) Seelye method; (2) Kinematic Wave; (3) SCS-TR-55. The designer must select the appropriate method for the site. A comprehensive discussion of each of these methods is beyond the scope of this participant guide. Other sources, such as SCS-TR-55 and VSWHB, can be consulted for more information.

The travel time for overland flow may be determined by using the following methods as appropriate. If the groundcover conditions are not homogenous for the entire overland flow path, determine the travel time for each groundcover condition separately and add the travel times to get overland flow travel time. Do not use an average groundcover condition.

NOTE:

The hydraulic length for overland flow should be determined for each site rather than assuming the maximum recommended length.

SEELYE METHOD:

Travel time for overland flow can be determined by using the Seelye chart (VSWHB; Appendix A, Figure A-4A - presented below). This method is perhaps the simplest and is most commonly used for small developments where a greater margin of error is acceptable. The figure on the next page shows a VDOT modified Seelye Chart that incorporates the Rational Method C-value.

Determine the length of overland flow and enter the nomograph on the left axis, "Length of Strip." Intersect the "Character of Ground" to determine the turn point on the "Pivot" line. Intersect the "Percent of slope", and read the travel time for overland flow.

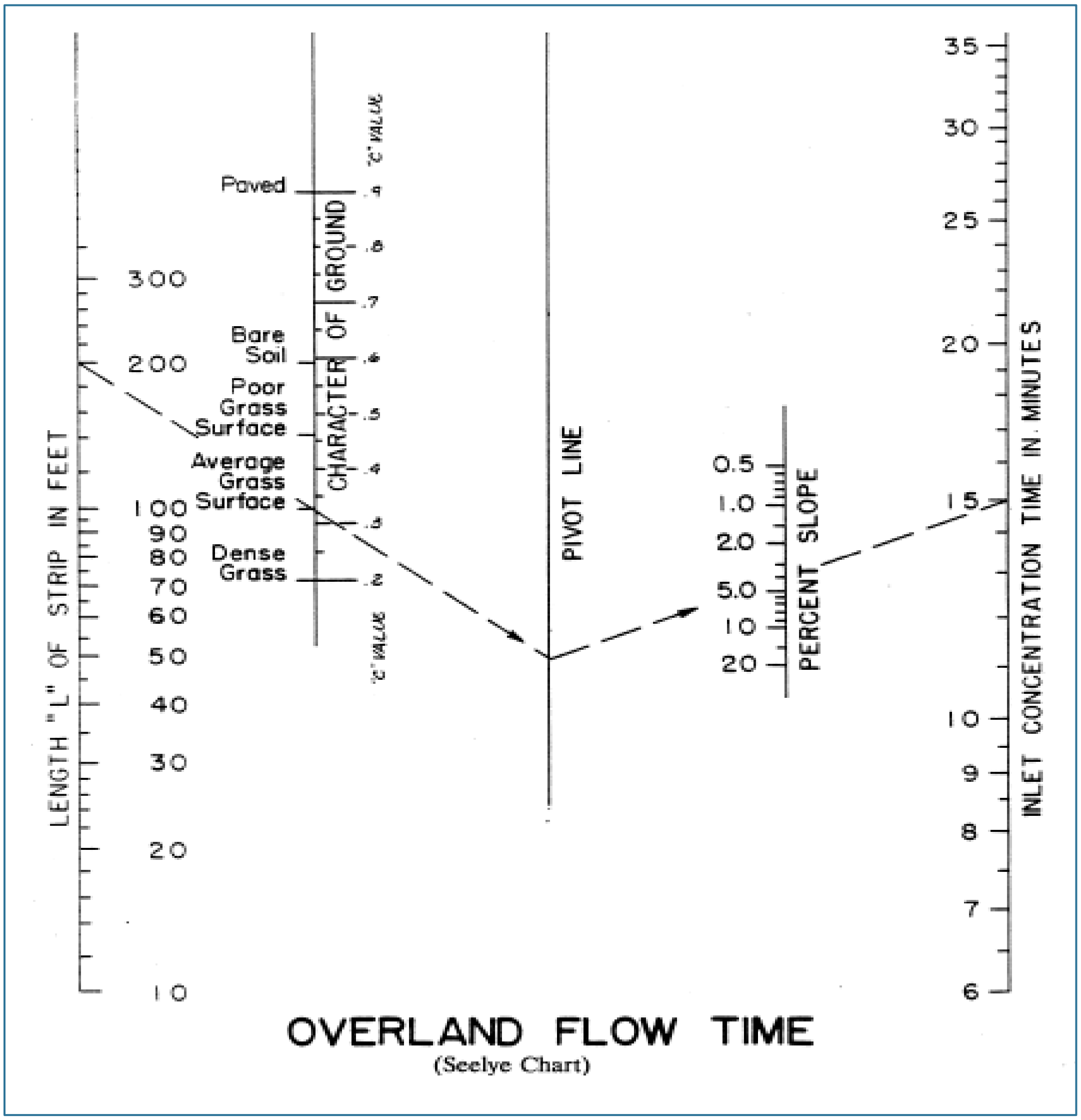
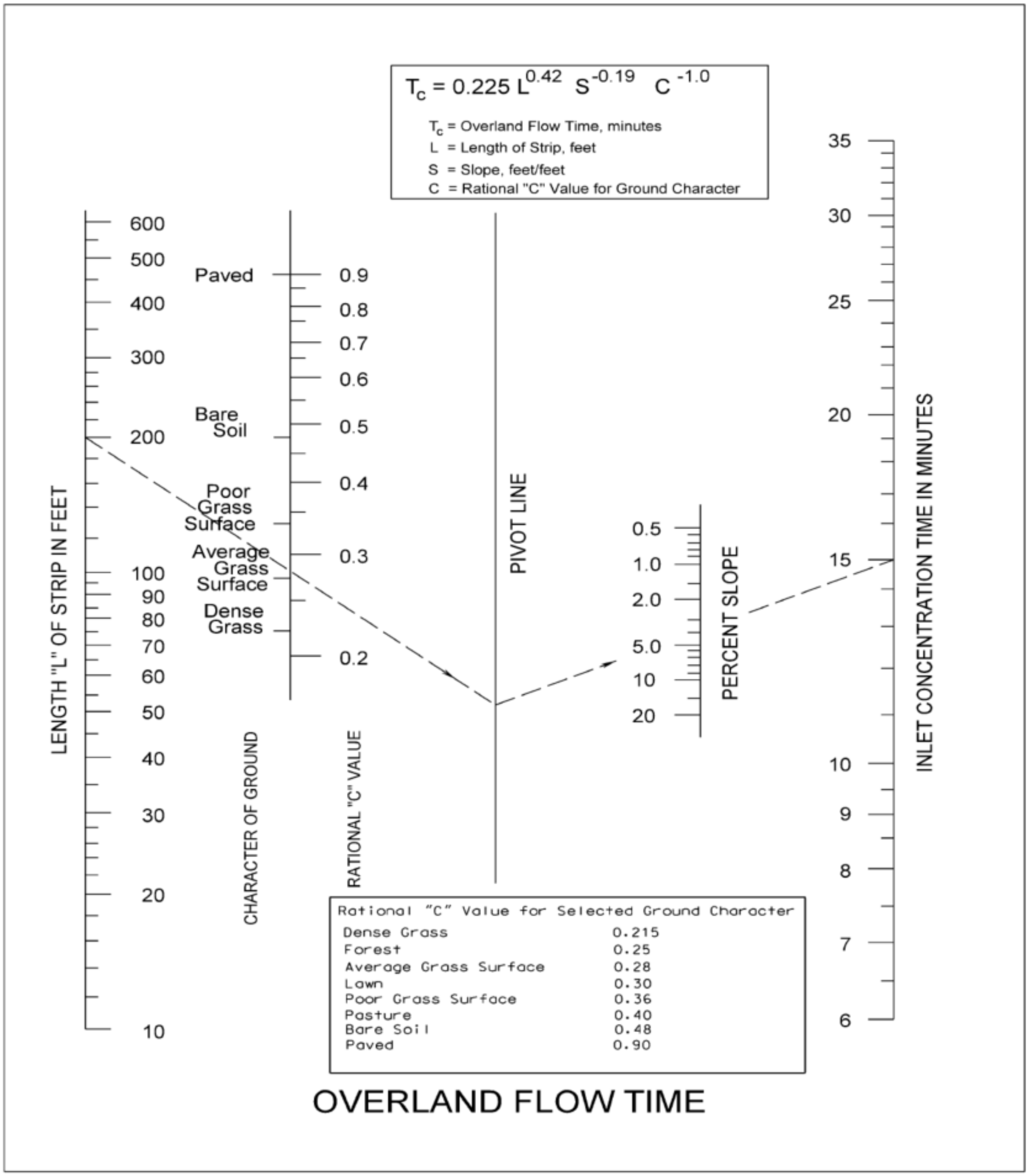


Figure 9-20: Seelye Chart (VSWHB)

VDOT Modified Seelye Chart



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2nd EDITION (1951) BY E. E. SEELYE

Figure 9-21: Overland Flow Seelye Chart using Rational Method C-value (VDOT Drainage Manual, Chapter 6)

KINEMATIC WAVE METHOD:

The Kinematic Wave method uses the following equation. It allows for the input of rainfall intensity values, thereby providing the specific overland flow travel time for the selected design storm.

$$Tt = 0.93 \times \frac{L^{0.6} \times n^{0.6}}{i^{0.4} \times S^{0.3}}$$

L = length of overland flow (feet)

n = Manning's roughness coefficient (Table A-1, VSWHB)

i = rainfall intensity (inches/hour) (NOAA Atlas 14)

Since the equation contains two unknown variables (travel time and rainfall intensity), a trial-and-error process is used to determine the overland flow time.

a) Assume a rainfall intensity value (from NOAA Atlas 14) and solve the equation for travel time (T_t).

b) Compare the assumed rainfall intensity value with the rainfall intensity value (from) that corresponds with the travel time.

c) If the assumed rainfall intensity value equals the corresponding rainfall intensity value, the process is complete. If not, adjust the assumed rainfall intensity value accordingly and repeat the procedure until the assumed value compares favorably with the corresponding rainfall intensity value. See VDOT Drainage Manual Chapter 6 for more details.

NRCS TR-55 METHOD

TR-55 utilizes Manning's kinematic solution to compute T_c for overland sheet flow.

NRCS TR-55 Method (Manning's Kinematic Equation)

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

Tt = travel time (hr)
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)

Manning's Kinematic Solution (TR-55, 1986)

See Module 10 and/or TR-55 documentation for more details.

The roughness coefficient is the primary culprit in the misapplication of the kinematic T_c equation due to the potential inaccurate identification of surface conditions for overland flow. Leaves, grass/vegetative groundcover, sticks, and other surface litter represent significant obstacles for the shallow depth of sheet flow (less than 0.1 feet) (WinTR-55, 2009). TR-55, Table 3-1 (TR-55, 1986) and VSWHB, Appendix A, Table A-1, provide selected coefficients for various surface conditions. Refer to TR-55 (1986) for the use of Manning's Kinematic Equation.

Shallow Concentrated Flow

Shallow concentrated flow begins where overland flow converges due to surface irregularities (uneven ground, litter, rocks, etc.) to form defined flow paths, which may include small rills or gullies. Shallow concentrated flow can occur due to natural depressional features, small man-made drainage ditches (paved and unpaved) and in curb and gutters. TR-55 provides a graphical solution for shallow concentrated flow.

- Assumption is that there is no well-defined channel, the flow depth is no greater than 0.5 feet, and the flow length is no greater than 1000 feet.
- Shallow concentrated flow travel time is calculated using the following equation:

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

Tt = Travel time (hours)
L = flow length (feet)
V = average velocity (feet/second)
t = conversion factor, 3,600 seconds/hr **or 60 seconds/min.**

- The input information needed to solve for this flow segment (specifically for the average velocity in the above equation) is the land slope and the surface condition (paved or unpaved) or more specifically represented by one of seven flow types (NEH, 2010):

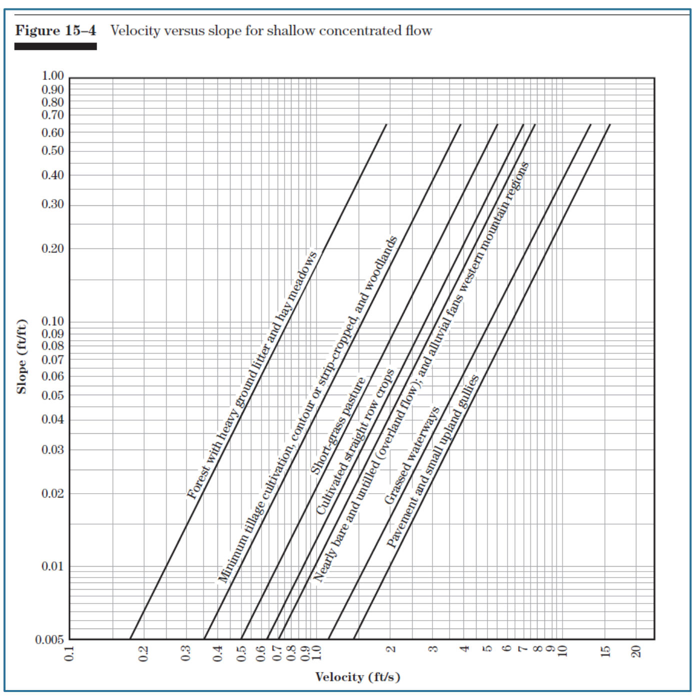


Figure 9-22: Velocity versus slope for shallow concentrated flow (TR-55, 1986)

- Slopes less than 0.005 foot per foot can use equations shown below in Table 9-2 (Table 15-3 from NEH, 2010):

Table 9-2: Shallow Concentrated Flow - Equations and Assumptions (NEH, 2010)

Table 15–3 Equations and assumptions developed from figure 15–4

Flow type	Depth (ft)	Manning's *n*	Velocity equation (ft/s)
Pavement and small upland gullies	0.2	0.025	$V = 20.328(s)^{0.5}$
Grassed waterways	0.4	0.050	$V=16.135(s)^{0.5}$
Nearly bare and untilled (overland flow); and alluvial fans in western mountain regions	0.2	0.051	$V=9.965(s)^{0.5}$
Cultivated straight row crops	0.2	0.058	$V=8.762(s)^{0.5}$
Short-grass pasture	0.2	0.073	$V=6.962(s)^{0.5}$
Minimum tillage cultivation, contour or strip-cropped, and woodlands	0.2	0.101	$V=5.032(s)^{0.5}$
Forest with heavy ground litter and hay meadows	0.2	0.202	$V=2.516(s)^{0.5}$

The initial paved vs unpaved slope-velocity curves presented in the 1986 release of TR-55 and shown below may have been sufficient at that time given that TR-55 was specifically recommended for use in evaluating urban hydrology, where it was assumed that shallow concentrated flow would primarily occur either in paved areas or in grassed areas (shown as unpaved below) and no other variations were needed.

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

Tt = Travel time (hours)

L = flow length (feet)

V = average velocity (feet/second)

t = conversion factor, 3,600 secs/hr or

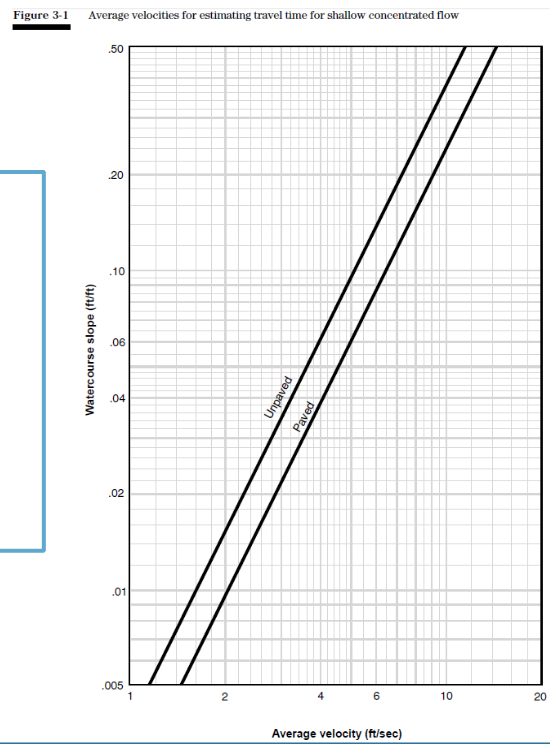


Figure 9-23: Unpaved and Paved average velocities of shallow concentrated flow (NEH, 2010)

The velocity method for computing time of concentration across a broader variety of land covers is applicable as presented above (Fig 15.4 of NEH 2010, Figure 9-23).

- Additional curves were developed as supplemental, using assumptions regarding flow shape, width, and depth:

Figure 15B–2 Cerrelli's and Humpal's shallow concentrated flow curves

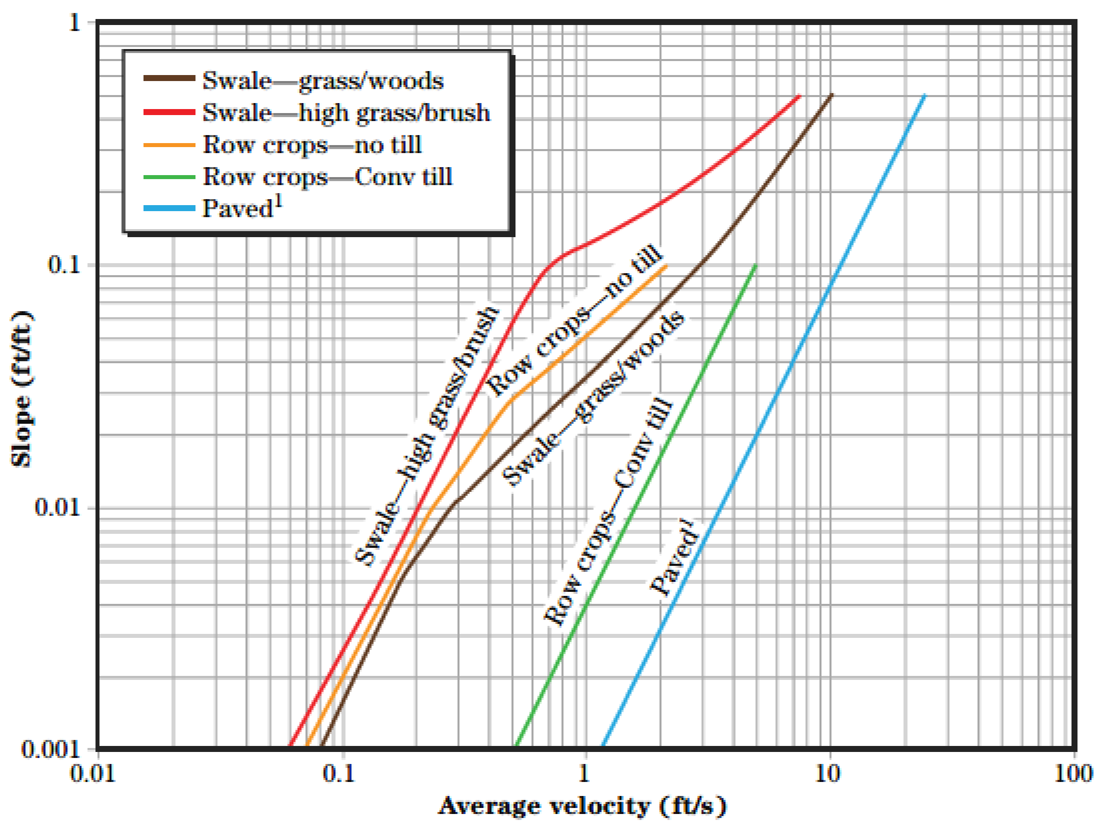


Table 15B–1 Assumptions used by Cerrelli and Humpal to develop shallow concentrated flow curves

Cover type	Flow shape	Width (ft)	Depth (ft)	Hydraulic radius, R (ft)	Retardance	*n* value
Wide swale—lawn/mature woods	Parabolic	10	0.4	0.27	D	
Wide swale—high grass/brushy	Parabolic	10	0.4	0.27	C	
Row crops—no till	Parabolic	7.5	0.3	0.23	D	
Row crops—conventional tillage/bare gully	Parabolic	7.5	0.3	0.23		0.035
Paved 1/	Triangular	12	0.4	0.19		0.014

1 The assumptions and limits for the paved condition used to define the paved line in figure 15B–2 are not the same as those used for the pavement and small upland gullies line shown in figure 15–4. Velocities obtained using figure 15–4 and/or table 15–3 should not be combined with those obtained from figure 15B–2.

Figure 9-24: Correli's and Humpall's Shallow Concentrated Flow (NEH, 2010)

Channel Flow

Channel flow occurs where flow converges in gullies, ditches, or swales, and natural or man-made 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. Manning's Equation is used for open channel flow and pipe flow and, usually, assumes full flow or bankfull velocity. Manning's coefficients can be found in TR-55, Table 4-9(b-d) for open channel flow (natural and man-made channels) and closed channel flow (TR-55, 1986). 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 coefficient
R = hydraulic radius (A/P)
A= wetted cross sectional area
P=wetted perimeter (ft)
s = slope (ft/ft)

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

Tt = Travel time (hours)
L = flow length (feet)
V = average velocity (feet/second)
t = conversion factor, 3,600 seconds/hr **or 60 seconds/min.**

→ *use Manning's equation*

Worksheet 3 from TR-55 (reproduced on the next page in Figure 9-25) provides an organized method for documenting inputs and computations for Time of Concentration (T_C) and Travel Time (T_T).

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

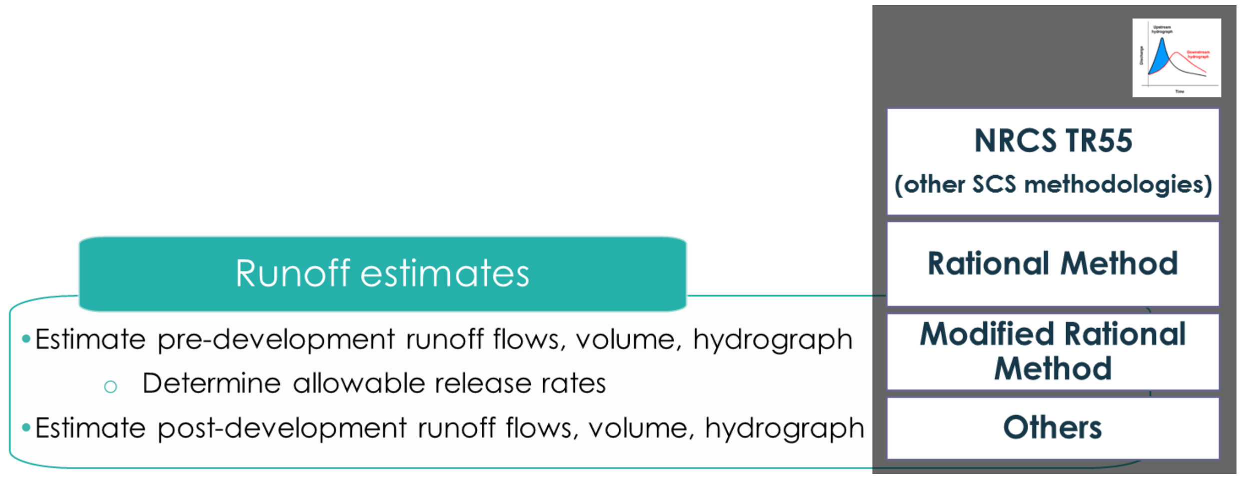
Segment ID				
12. Cross sectional flow area, a .... ft^2				
13. Wetted perimeter, p_w .... ft				
14. Hydraulic radius, $r = \dfrac{a}{p_w}$ Compute r .... ft				
15 Channel slope, s .... ft/ft				
16. Manning's roughness coefficient, n				
17. $V = \dfrac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ....ft/s				
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 9-25: Worksheet 3 Time of Concentration or Travel Time (TR55, 1986)

Time of Concentration Limitations

- Overland flow should be limited to 100 feet or less, based on current guidance given in WinTR-55, NEH (2010), the VSWHB, and DEQ policy. This guidance has been developed based on a review of numerous technical papers on sheet flow.
- For watersheds with storm sewers, T_c will require that care be taken to accurately identify the hydraulic flow path.
- A culvert or bridge can act as a detention structure if there is significant storage behind it. Detailed storage routing procedures can be used to determine the outflow through the culvert or bridge and will result in a reduction of the peak discharge.
- The minimum T_c used in TR-55 is 5 minutes or 0.1 hour.

9e. Runoff Estimation Methods



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:

Rational Formula

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

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

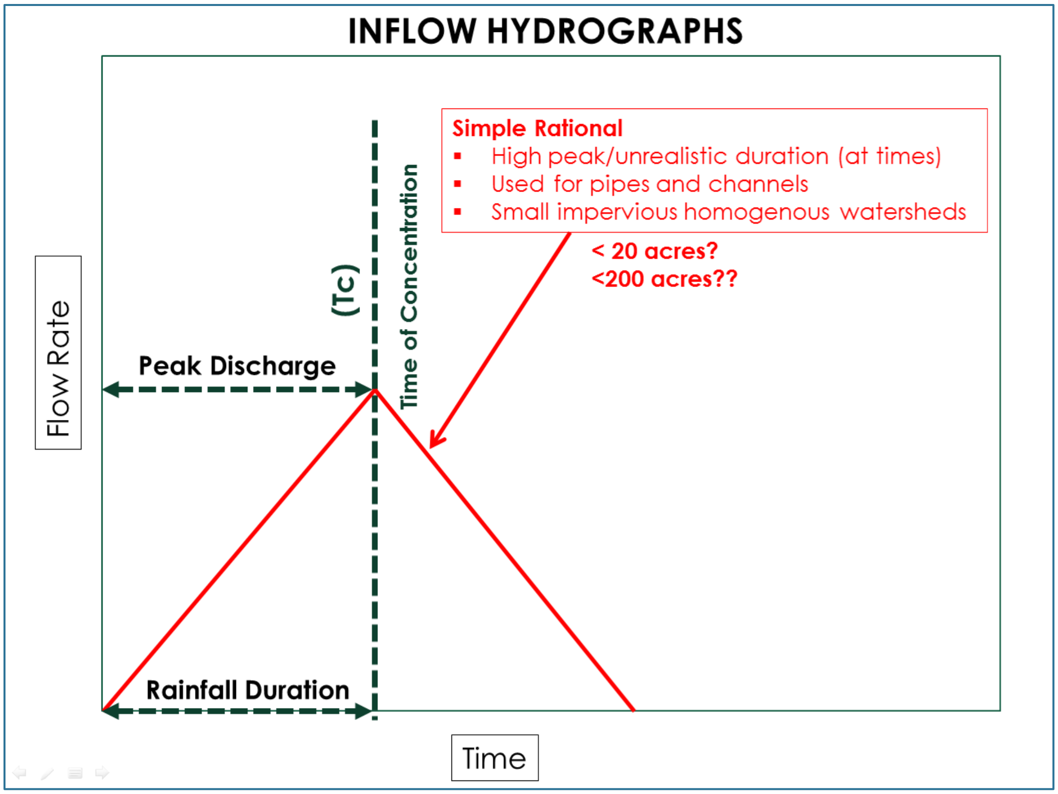


Table 9-3: Rational Formula Runoff Coefficients (VDOT)

Rational Method Coefficients

C_{Cf} Values for 10 Year Storm Frequency (C_f=1.0)

Land Use		Average Watershed Slope: Flat <2%	Rolling 2% - 6%	Steep >6%	Average % Impervious
Business, Commercial & Industrial		0.8	0.85	0.90	90%
Apartments and Townhomes		0.65	0.70	0.75	75%
Schools		0.50	0.55	0.60	50%
Residential	lots 10,000 sq. ft	0.40	0.45	0.50	35%
	lots 12,000 sq. ft.	0.40	0.43	0.45	30%
	lots 17,000 sq. ft.	0.35	0.40	0.45	25%
	lots ½ acre or more	0.30	0.35	0.40	20%
Parks, Cemeteries and Unimproved Areas		0.20	0.28	0.35	15%
Paved and Roof Areas			0.90		100%
Cultivated Areas		0.50	0.60	0.70	Varies
Pasture		0.35	0.40	0.45	Varies
Lawns		0.25	0.30	0.35	Varies
Forest		0.20	0.25	0.30	Varies
Railroad Yard Areas		0.20	0.30	0.40	
Roadway Slopes (2:1) w/ Little or No Vegetated Cover			0.70		
Roadway Shoulder & Ditch Areas w/ Little or No Vegetated Cover			0.50		
Roadway Slopes (2:1) w/ Established Vegetated Cover			0.40		
Roadway Shoulder & Ditch Areas w/ Established Vegetated Cover			0.35		

Table 9-4: Rational Formula Runoff Coefficients and TR-55 Curve Numbers (VDOT)

RATIONAL METHOD "C" VALUES		N.R.C.S. "TR-55" METHOD "CN" VALUES					
LAND COVER	RUNOFF COEFICIENT "C"	COVER TYPE & HYDROLOGIC CONDITION	Avg.% Imp.	Curve Numbers for Hydrologic Soil Group*			
				A	B	C	D
Business, industrial and commercial	0.80 to 0.90	Commercial and business	85	89	92	94	95
		Industrial	72	81	88	91	93
Residential	0.40 to 0.50	Residential area by lot size:					
		1/8 acre or less (town houses)	65	77	85	90	92
lots 10,000 sq. ft.	0.40 to 0.45	¼ acre	38	61	75	83	87
- lots 12,000 sq. ft.		1/3 acre	30	57	72	81	86
- lots 17,000 sq. ft.	0.35 to 0.45	½ acre	25	54	70	80	85
- lots ½ ac. or more		1 acre	20	51	68	79	84
	0.30 to 0.40	2 acres	12	46	65	77	82
		Farmsteads – buildings, lanes, driveways, and surrounding lots	n.a.	59	74	82	86
Parks, cemeteries and unimproved areas	0.20 to 0.35	Open space (lawns, parks, golf courses Cemeteries, etc.) grass cover > 75%	n.a.	39	61	74	80
Lawns	0.20 to 0.40						
Paved and roof areas	0.9	Streets & roads:					
		Paved parking lots, roofs, driveways, etc.	n.a.	98	98	98	98
		Paved: open ditches (excluding R/W)	n.a.	83	89	92	93
		Gravel (including R/W)	n.a.	76	85	89	91
		Dirt (including R/W)	n.a.	72	82	87	89
Cultivated areas	0.50 to 0.70	Cultivated areas (combination of straight & Row crops)	n.a.	71	80	87	90
Pasture	0.35 to 0.45	Pasture, grassland, or range	n.a.	39	61	74	80
		Meadow – continuous grass	n.a.	30	58	71	78
		Brush-brush-weed-grass mixture with brush the major element	n.a.	30	48	65	73
Forest	0.20 to 0.30	Woods	n.a.	30	55	70	77
		Woods/grass combination	n.a.	32	58	72	79

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 affect 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, more rigorous procedures for determining the time of concentration are typically recommended. Some of which were identified earlier and are found in the VSWHB or Chapter 15, Part 630 of the NRCS National Engineering Handbook (NEH, 2010).

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. ***The older version IDF curves derived from the TP40 rainfall data are available in several resources but should not be used any longer as more accurate and up-to-date data is available through NOAA Atlas 14. VDOT uses B, D, and E factors, which are county specific, to define intensity for use with the Rational and Modified Rational methods (See Chapter 6 of the VDOT Drainage Manual). IDF values may be found using the methods below:***

B, D and E Factors that Define Intensity-Duration-Frequency (IDF) Values*
for Use with the Rational Method and the Modified Rational Method

The rainfall IDF values are described by the equation:

$$i = \frac{B}{(t_c + D)^E}$$

Where:

i = Intensity, inches per hour (in/hr)
t_c = Time of concentration, minutes (min)

Table 9-5: Subset of B, D, and E Factors (VDOT)

Chapter 6 - Hydrology

Appendix 6C-2 B, D, and E Factors

B. D. & E factors for determining rainfall intensity in the Rational and Modified Rational Methods (based on NOAA NW-14 Atlas data)

STATION	ID	1-YR			2-YR			5-YR			10-YR		
		B	*D*	*E*	*B*	*D*	*E*	*B*	*D*	*E*	*B*	*D*	*E*
Richardsville	44-7164	43.52	11.05	0.84	52.84	11.40	0.84	57.42	11.52	0.81	59.21	11.23	0.78
Richmond WB City	44-7206	46.49	11.09	0.84	54.21	11.19	0.83	58.15	11.23	0.80	59.29	10.90	0.77
Richmond WSO Airport	44-7201	46.27	11.01	0.84	54.61	11.24	0.83	59.16	11.40	0.80	59.77	10.92	0.78
Riverton	44-7254	37.30	9.34	0.84	44.53	9.59	0.83	48.63	9.34	0.80	49.29	8.68	0.77
Roanoke	44-7275	38.05	10.85	0.84	45.84	11.22	0.83	50.67	11.22	0.80	52.24	10.93	0.78

An example of using the VDOT intensity equation above and the B, D, and E factors from Table 9-5 above would be for a 1-year storm with a time of concentration of 5 minutes at the Richmond WSO Airport:

$$i = 46.27/(5+11.01)^{.84}$$

$$i = 4.50 \text{ in/hr}$$

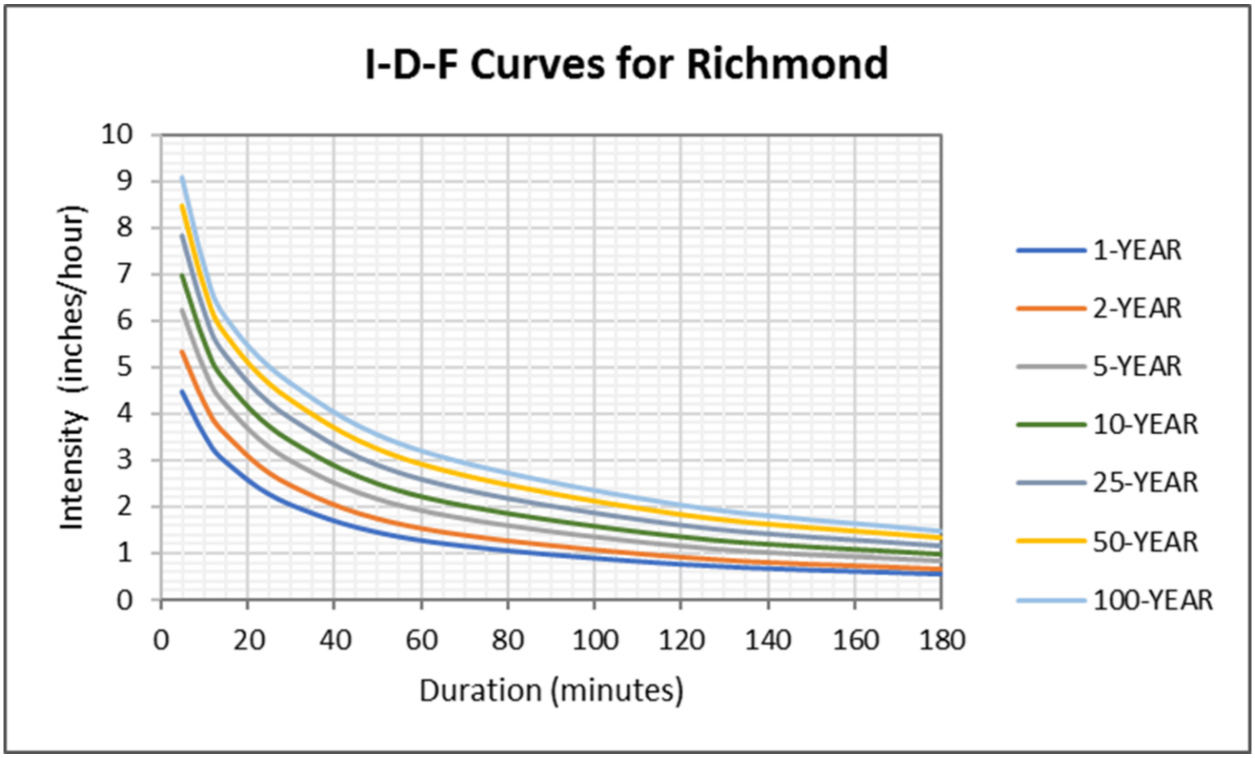


Figure 9-26: Old Format Intensity Duration Frequency Curve for Richmond (NOAA Atlas 14)

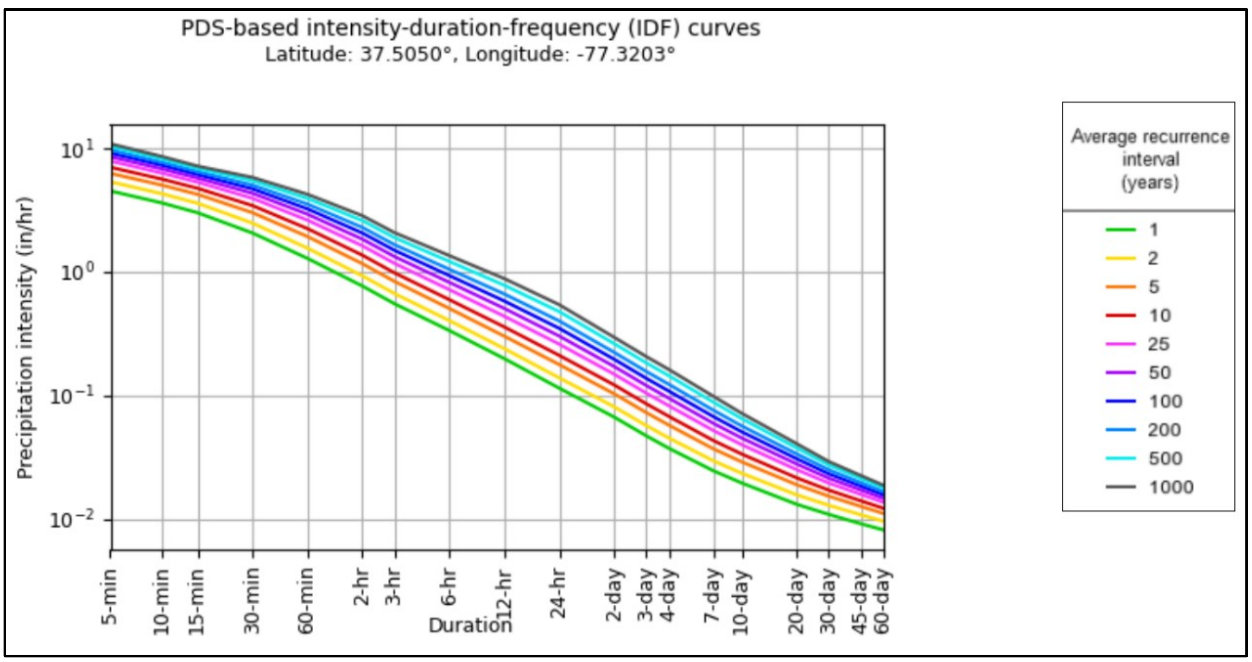


Figure 9-27: New Format Intensity Duration Frequency Curve for Richmond (NOAA Atlas 14)

In the example (Figure 9-27) above, the newer format I-D-F curves from NOAA Atlas 14 show precipitation intensity on the vertical Y-axis where 10^1 represents 10 inches, 10^0 represents 1 inch, 10^{-1} represents 0.1 inches, and 10^{-2} represents 0.01 inches.

An example using NOAA Atlas 14 to determine rainfall intensity using either the tabular form or the graphical I-D-F curves is included below:

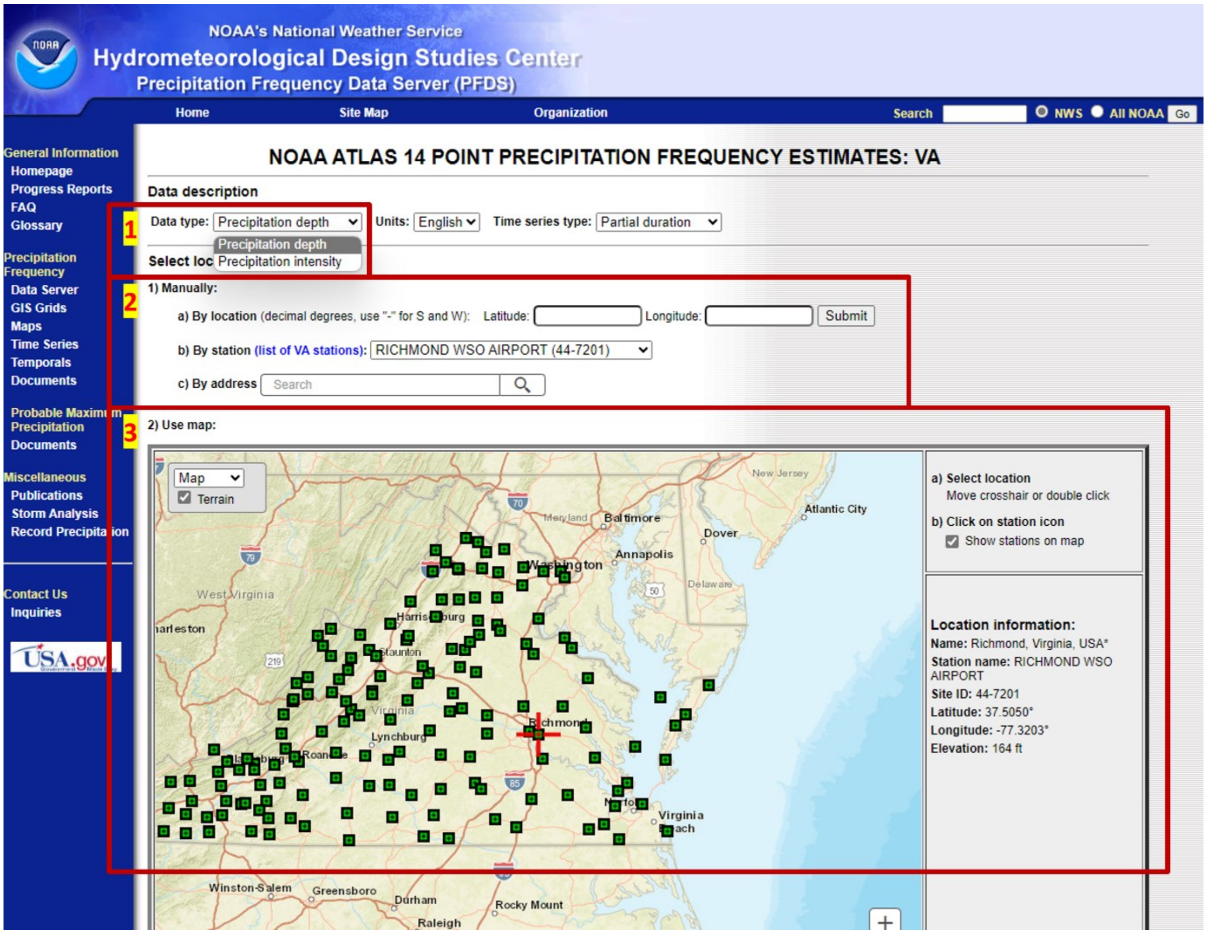


Figure 9-28: NOAA Atlas 14 Precipitation Intensity

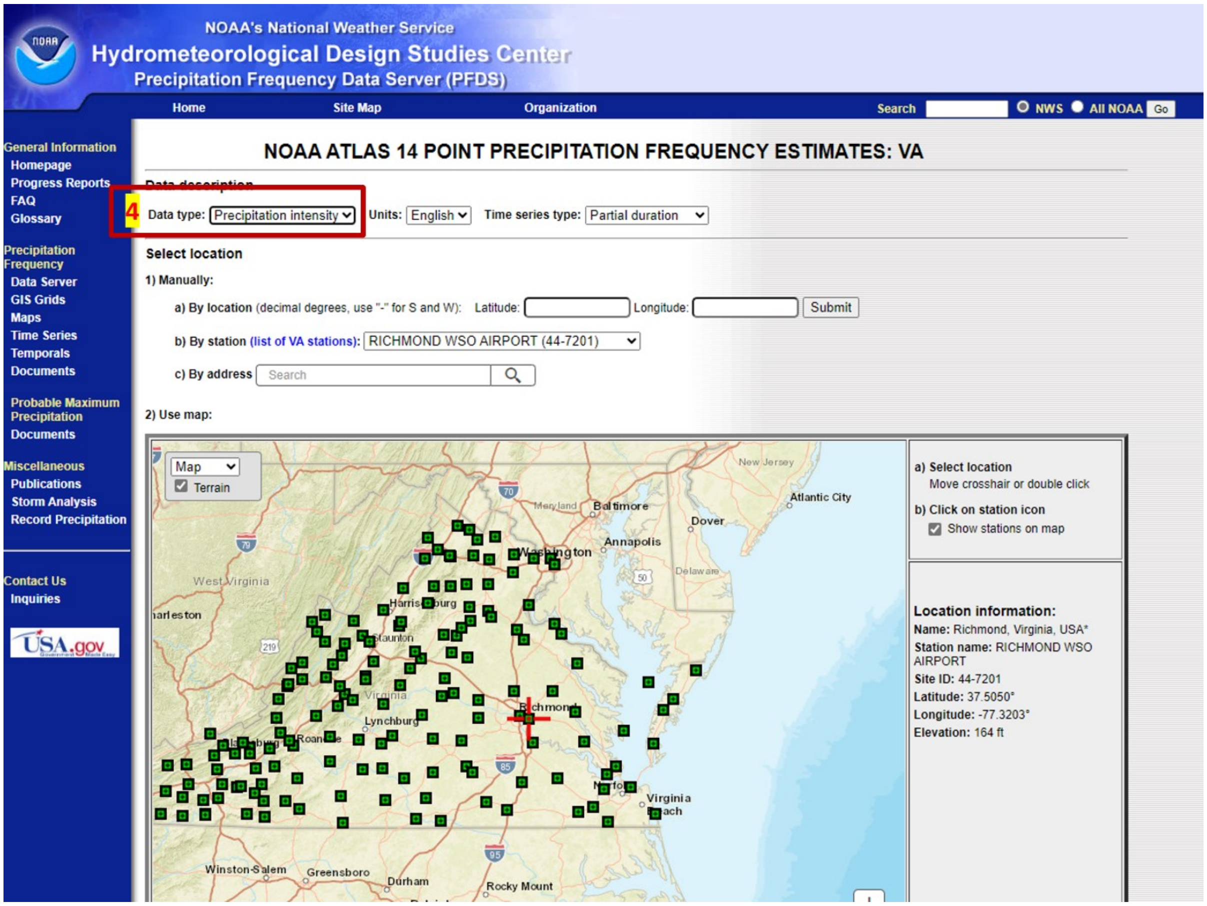


Figure 9-29: NOAA Atlas 14 Precipitation Intensity Updated

The NOAA Atlas 14 homepage defaults to Precipitation depth as the “Data type”, but the arrow can be used to open a drop-down menu (1) where Precipitation intensity can be selected (4), which will then update the webpage with precipitation intensity data vs precipitation depth data. Like the previous NOAA Atlas 14 example (Figure 9-14), four choices for identifying the site area are available (2): by latitude and longitude, station, or site address. The fourth option (3) is by selecting a specific point on the map. In the example above (Figure 9-29), selecting a station is shown both in (2) and the map view (3); however, for the most accurate site data the designer and/or plan reviewer should use the latitude and longitude (2a) or the site address (2c).

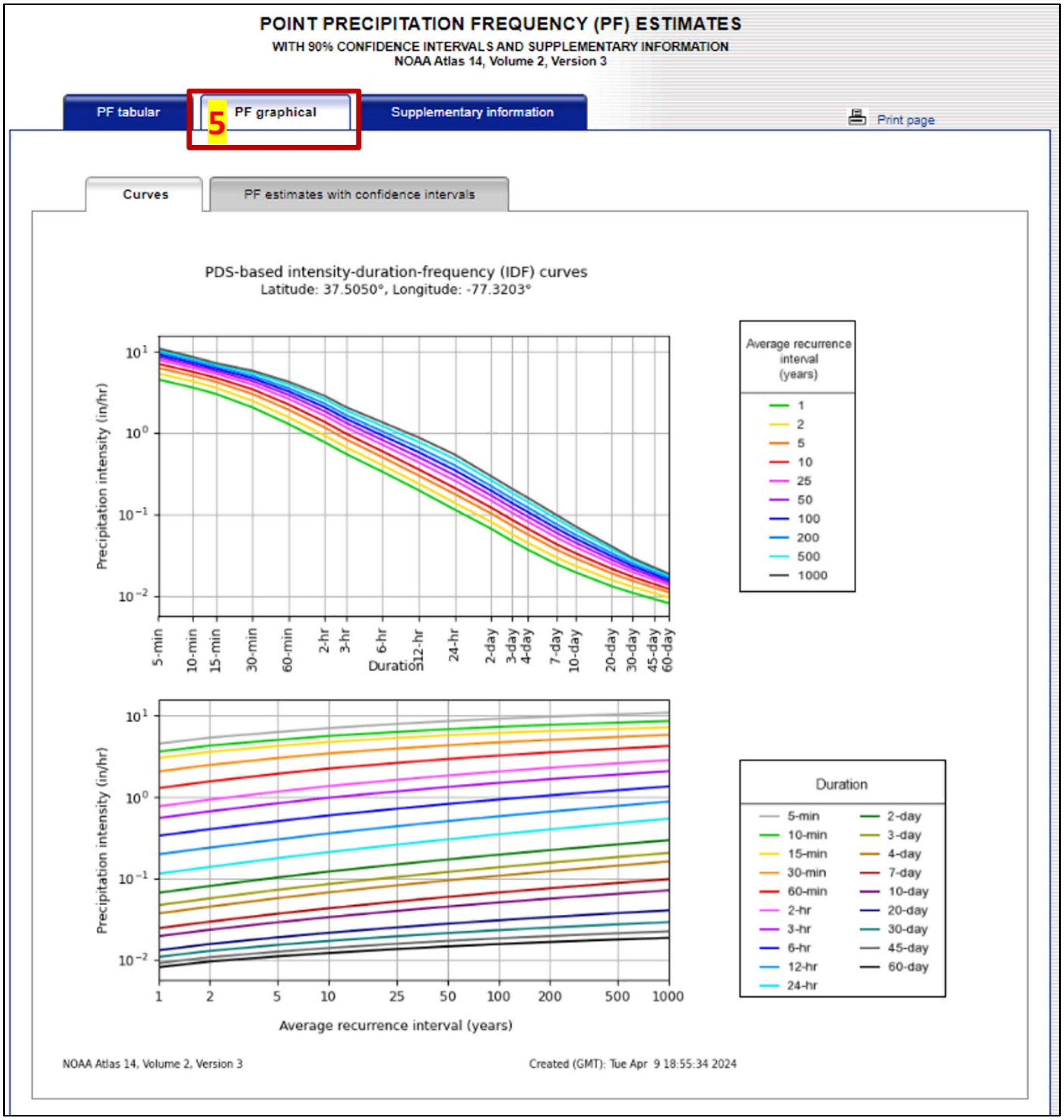


Figure 9-30: NOAA Atlas 14 Precipitation I-D-F Curves

By selecting the PF Graphical tab (5), the IDF curves for a site will be generated (Figure 9-30). Another option for determining the precipitation intensity is by using the PF tabular (6) chart (Figure 9-31). For compliance with VESMA and the VESM Regulation, the 24-hour storm event (8) should be used for the appropriate recurrence interval design storm event (1-, 2-, and 10-year) highlighted below. However, for the rational method the storm duration is equal to the time of concentration (7), which highlights the Rational Method's limitation for use with program compliance.

POINT PRECIPITATION FREQUENCY (PF) ESTIMATES

WITH 90% CONFIDENCE INTERVALS AND SUPPLEMENTARY INFORMATION

NOAA Atlas 14, Volume 2, Version 3

6 PF tabular | PF graphical | Supplementary information | Print page

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
7 5-min	**4.51** (4.10-4.96)	**5.35** (4.88-5.88)	**6.26** (5.71-6.89)	**7.02** (6.37-7.72)	**7.88** (7.13-8.63)	**8.53** (7.69-9.35)	**9.14** (8.20-10.0)	**9.70** (8.64-10.6)	**10.4** (9.16-11.4)	**10.9** (9.54-12.0)
10-min	**3.60** (3.28-3.95)	**4.28** (3.91-4.70)	**5.02** (4.58-5.51)	**5.62** (5.10-6.17)	**6.28** (5.68-6.88)	**6.79** (6.13-7.44)	**7.27** (6.51-7.96)	**7.69** (6.85-8.41)	**8.19** (7.24-8.99)	**8.56** (7.51-9.41)
15-min	**3.00** (2.73-3.30)	**3.58** (3.27-3.94)	**4.23** (3.86-4.65)	**4.74** (4.30-5.20)	**5.31** (4.80-5.81)	**5.73** (5.17-6.28)	**6.12** (5.49-6.71)	**6.46** (5.76-7.08)	**6.87** (6.08-7.54)	**7.16** (6.29-7.87)
30-min	**2.06** (1.87-2.26)	**2.48** (2.26-2.72)	**3.01** (2.74-3.30)	**3.43** (3.12-3.77)	**3.93** (3.55-4.30)	**4.32** (3.89-4.73)	**4.69** (4.20-5.14)	**5.03** (4.49-5.51)	**5.47** (4.83-6.00)	**5.80** (5.09-6.37)
60-min	**1.28** (1.17-1.41)	**1.55** (1.42-1.71)	**1.93** (1.76-2.12)	**2.23** (2.03-2.45)	**2.62** (2.37-2.87)	**2.92** (2.64-3.20)	**3.23** (2.89-3.54)	**3.53** (3.15-3.86)	**3.92** (3.47-4.30)	**4.24** (3.72-4.65)
2-hr	**0.766** (0.694-0.846)	**0.927** (0.843-1.02)	**1.16** (1.05-1.28)	**1.36** (1.23-1.50)	**1.62** (1.46-1.78)	**1.84** (1.64-2.02)	**2.06** (1.82-2.25)	**2.28** (2.01-2.50)	**2.59** (2.26-2.84)	**2.84** (2.46-3.12)
3-hr	**0.550** (0.497-0.611)	**0.666** (0.603-0.737)	**0.835** (0.755-0.925)	**0.979** (0.883-1.08)	**1.17** (1.05-1.29)	**1.33** (1.18-1.46)	**1.49** (1.32-1.64)	**1.66** (1.45-1.82)	**1.88** (1.64-2.07)	**2.07** (1.78-2.28)
6-hr	**0.333** (0.300-0.373)	**0.401** (0.362-0.449)	**0.504** (0.452-0.562)	**0.593** (0.530-0.661)	**0.715** (0.636-0.795)	**0.819** (0.723-0.908)	**0.929** (0.814-1.03)	**1.05** (0.908-1.16)	**1.21** (1.04-1.34)	**1.35** (1.14-1.49)
12-hr	**0.197** (0.178-0.222)	**0.238** (0.215-0.267)	**0.300** (0.270-0.337)	**0.357** (0.319-0.399)	**0.436** (0.386-0.485)	**0.504** (0.442-0.561)	**0.579** (0.502-0.641)	**0.659** (0.565-0.729)	**0.777** (0.654-0.859)	**0.879** (0.730-0.970)
8 24-hr	**0.114** (0.104-0.125)	**0.138** (0.126-0.152)	**0.177** (0.162-0.194)	**0.210** (0.191-0.231)	**0.259** (0.234-0.284)	**0.301** (0.271-0.329)	**0.347** (0.310-0.379)	**0.399** (0.353-0.434)	**0.475** (0.415-0.517)	**0.540** (0.466-0.588)
2-day	**0.066** (0.060-0.072)	**0.080** (0.073-0.088)	**0.102** (0.094-0.112)	**0.121** (0.110-0.132)	**0.148** (0.134-0.161)	**0.170** (0.153-0.186)	**0.195** (0.174-0.213)	**0.222** (0.197-0.243)	**0.261** (0.229-0.286)	**0.294** (0.255-0.322)
3-day	**0.046** (0.043-0.051)	**0.056** (0.052-0.062)	**0.072** (0.066-0.079)	**0.085** (0.078-0.093)	**0.104** (0.094-0.113)	**0.119** (0.108-0.130)	**0.137** (0.122-0.149)	**0.155** (0.138-0.169)	**0.182** (0.160-0.199)	**0.205** (0.178-0.225)
4-day	**0.037** (0.034-0.040)	**0.044** (0.041-0.049)	**0.057** (0.052-0.062)	**0.067** (0.061-0.073)	**0.082** (0.074-0.089)	**0.094** (0.085-0.102)	**0.107** (0.097-0.117)	**0.122** (0.109-0.133)	**0.143** (0.126-0.156)	**0.161** (0.140-0.176)
7-day	**0.024** (0.022-0.026)	**0.029** (0.027-0.032)	**0.036** (0.033-0.040)	**0.042** (0.039-0.046)	**0.051** (0.047-0.056)	**0.059** (0.053-0.064)	**0.067** (0.060-0.073)	**0.075** (0.067-0.082)	**0.087** (0.077-0.096)	**0.097** (0.086-0.107)
10-day	**0.019** (0.018-0.021)	**0.023** (0.021-0.025)	**0.028** (0.026-0.031)	**0.033** (0.030-0.036)	**0.039** (0.036-0.043)	**0.045** (0.041-0.048)	**0.050** (0.046-0.054)	**0.056** (0.051-0.061)	**0.064** (0.057-0.070)	**0.071** (0.063-0.077)
20-day	**0.013** (0.012-0.014)	**0.015** (0.014-0.016)	**0.018** (0.017-0.020)	**0.021** (0.019-0.023)	**0.024** (0.023-0.026)	**0.027** (0.025-0.029)	**0.030** (0.028-0.032)	**0.033** (0.030-0.036)	**0.037** (0.033-0.040)	**0.040** (0.036-0.043)
30-day	**0.010** (0.010-0.011)	**0.012** (0.012-0.013)	**0.015** (0.014-0.016)	**0.017** (0.015-0.018)	**0.019** (0.018-0.020)	**0.021** (0.019-0.022)	**0.023** (0.021-0.024)	**0.024** (0.023-0.026)	**0.027** (0.025-0.029)	**0.029** (0.026-0.031)
45-day	**0.009** (0.008-0.009)	**0.010** (0.010-0.011)	**0.012** (0.011-0.013)	**0.013** (0.013-0.014)	**0.015** (0.014-0.016)	**0.017** (0.015-0.018)	**0.018** (0.017-0.019)	**0.019** (0.018-0.020)	**0.021** (0.019-0.022)	**0.022** (0.020-0.023)
60-day	**0.008** (0.007-0.008)	**0.009** (0.008-0.010)	**0.011** (0.010-0.011)	**0.012** (0.011-0.012)	**0.013** (0.012-0.014)	**0.014** (0.013-0.015)	**0.015** (0.014-0.016)	**0.016** (0.015-0.017)	**0.017** (0.016-0.018)	**0.018** (0.017-0.019)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Estimates from the table in CSV format: Precipitation frequency estimates | Submit

Figure 9-31: NOAA Atlas 14 Precipitation I-D-F Tabular Graphic

Using the same scenario above (Figure 9-30), focusing on a 1-year storm with a time of concentration of 5 minutes, we see the result of 4.51 (7). When comparing the different methods, the VDOT intensity equation provided above, the I-D-F curves (Figure 9-30), and the tabular chart (Figure 9-31) all produce similar results.

- VDOT intensity equation results: I =4.50 (Page 59)
- Tabular Chart results (7): I =4.51 (reasonable range 4.10-4.96)

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) are presented on pages 56 and 57 in Table 9-3 and Table 9-4.

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 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.

Weighted Runoff Coefficient (C)

Many projects will consist of drainage area where multiple land uses with different C values apply. In such instances, a weighted C value can be calculated:

Example 9-1:

What is the weighted C value for a 10-acre drainage area with 2 different land uses?

2 acres of parking lot (C=0.95)

8 acres of park area (C=0.25)

Solution:

1. Calculate $(C \times A)$ for each land use:

   $C_{lot} \times A_{lot} = 0.95 \times 2 = 1.9$

   $C_{park} \times A_{park} = 0.25 \times 8 = 2.0$

2. Add $(C \times A)$ values together and divide sum by total area to:

$$C_{weighted} = \frac{\left(CA_{lot} + CA_{park}\right)}{total\ area}$$

$$= \frac{(1.9 + 2.0)}{10}$$

$$= 0.39$$

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:

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

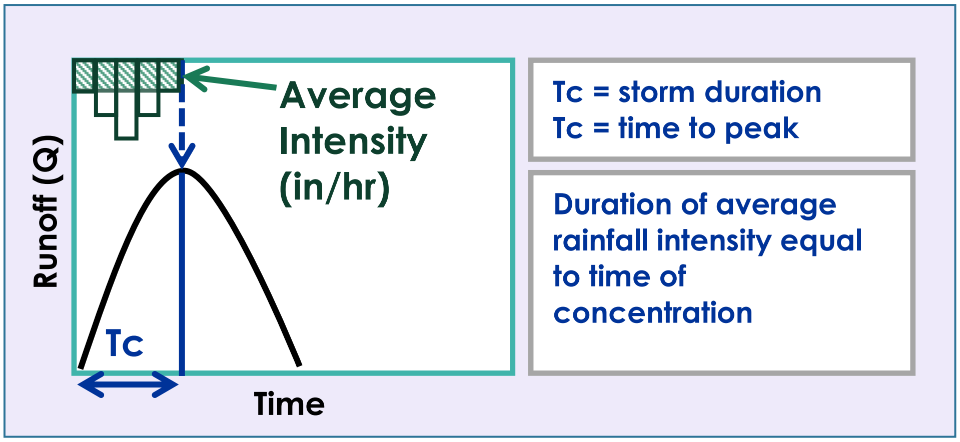
C_f values are provided in Table 9-6

Table 9-6: Rational Formula Frequency Factors (VDOT)

Recurrence Interval (Years)	C_f
1, 2, 5, and 10	1.0
25	1.1
50	1.2
100	1.25

Note: C_f multiplied by C should not exceed 1.0

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. In addition, 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 storm duration and equals the time to reach peak discharge.*

   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 on not only 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 is discussed earlier in this module.

   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 VESM Regulation at 9VAC25-875-620.

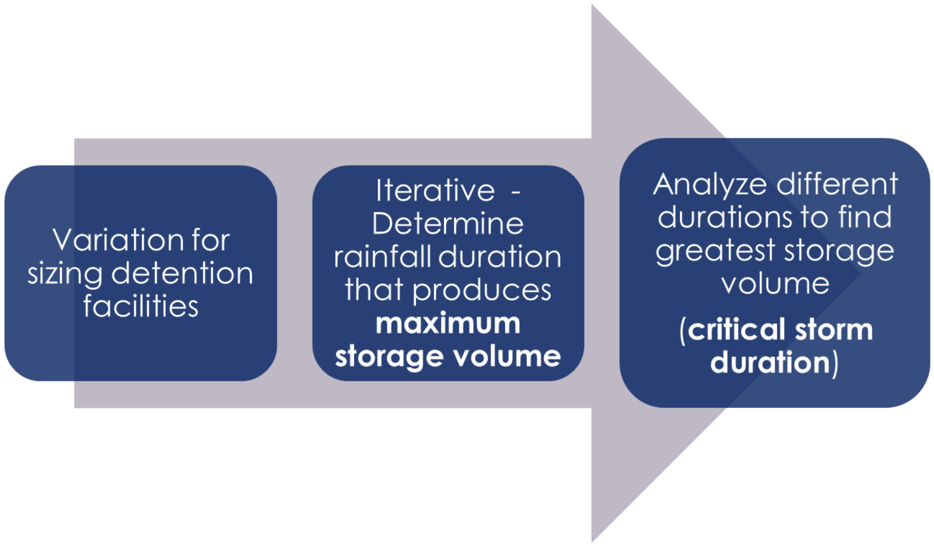
For larger watersheds, attenuation of peak flows through the drainage network begins to be a factor in determining peak discharge. For larger or more complex watersheds, it is better to use a hydrograph method or computer simulation in order to more accurately represent the discharge.

Similarly, the presence of bridges, culverts, or storm sewers may act as restrictions that ultimately affect 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 that 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 second only
- Not based on 24-hr storm duration
- Useful for design of culverts, inlets, etc.
- No volume determination
- Not well suited for VESMP compliance

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 allows the user to select a rainfall duration to meet specific purposes. 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 that produces the maximum storage volume requirement when sizing a detention basin.

Modified Rational Method Design Parameters

The equation Q = C x I x A (rational formula) is used to calculate the peak discharge. 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, in order 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 that 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 9-32 shows a family of hydrographs representing storms of different durations. The storm duration that 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 1.5 times T_c 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, discussed later in this module, 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.

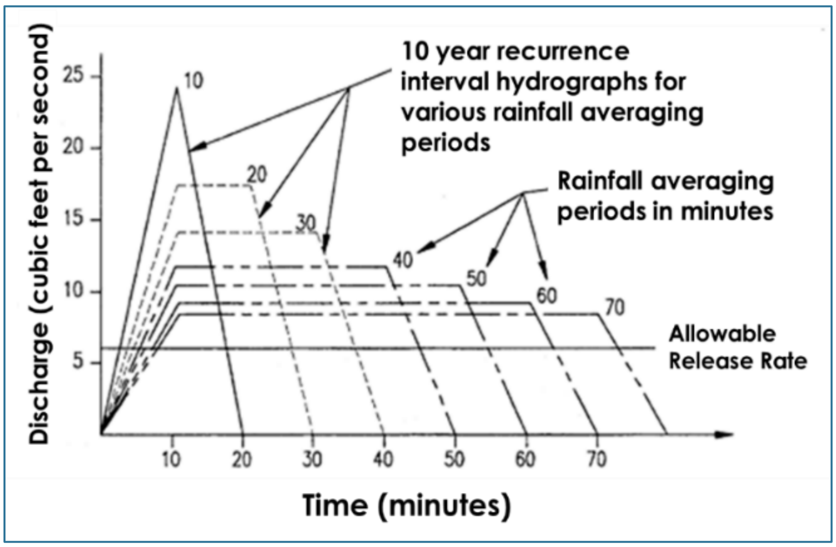


Figure 9-32: Modified Rational Method Runoff Hydrographs (VSWHB)

Modified Rational Method Assumptions

The modified rational method is based on the following assumptions:

1. *All 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 not included. 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 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.

Modified Rational Example

Modified Rational Method Maximum Storage Volume Calculations

Duration of Storm (min)	Intensity (in/hr)	Peak ▲ Flow(cfs)	Runoff ■ Volume (ft^3)	Release Volume ● (ft^3)	Required ▲ Storage Volume (ft^3)
15	4.8	39.9	35,925	828	35,097
30	3.4	28.3	50,894	1,656	49,238
45	2.7	22.5	60,624	2,484	58,140
60	2.3	19.1	68,856	3,312	65,544
90	1.7	14.1	76,341	4,968	71,373
120	1.4	11.6	83,825	6,624	77,201
180	1.1	9.1	98,794	9,936	**88,858**
210	0.9	7.3	94,303	11,592	82,711

Maximum Storage Volume Required

▲ Peak flow = Q = CIA Example: 0.7 x 4.8 in/hr x 11.88 acres = 39.9 cfs

■ Runoff Volume = Q x Storm Duration Example: 39.9 cfs x 15 min x 60 sec/min = 35,925 cf

● Release Volume = Allowable release rate x Storm Duration Example: 0.92 cfs x 15 min. x 60 sec./min = 828 cf

▲ Required Storage = Runoff Volume - Release Volume Example: 35,925 cf -828 cf = 35,097 cf

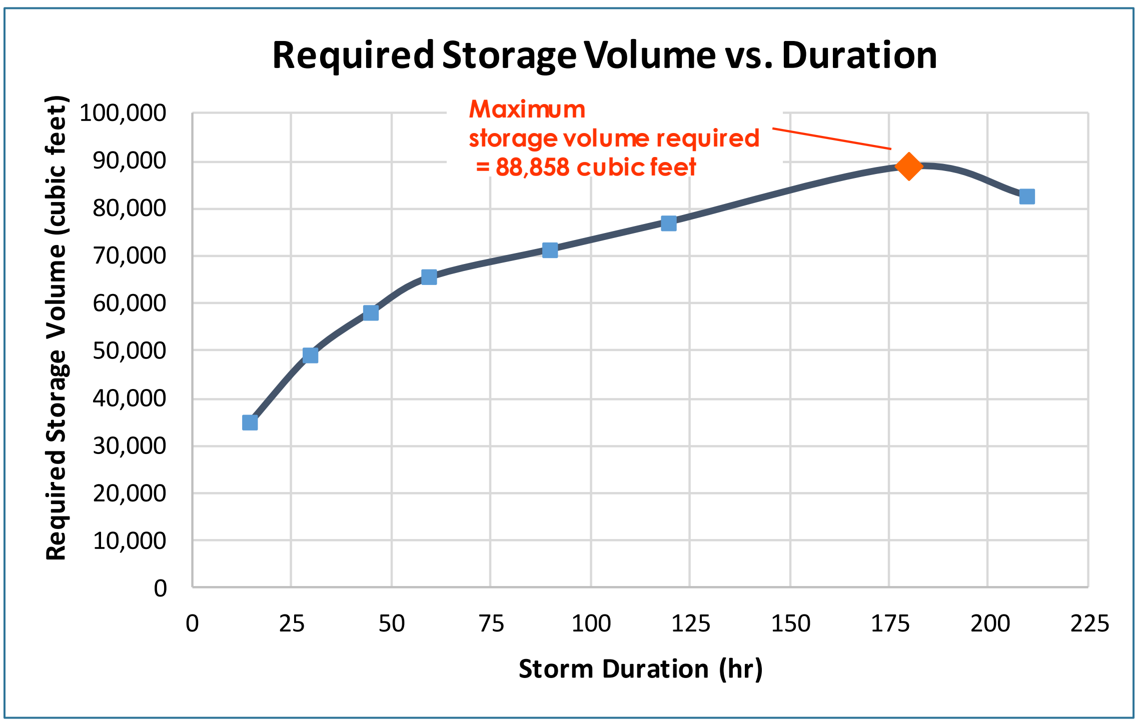


Figure 9-33: Modified Rational Routing Storage Volume vs. Duration Curve

Modified Rational Method-Direct Solution

As an alternative to the time intensive, iterative process of generating multiple hydrographs for the Modified Rational Method, a direct solution for the Critical Storm Duration has been developed. A full explanation of the Modified Rational Method-Critical Storm Duration Method is found in Chapter 11 of the VDOT Drainage Manual at https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/technical-guidance-documents/location-and-design/migrated/drainagemanual/DrainManual_Chapter11_acc10272023_PM.pdf. As with the hydrograph method described previously, the critical storm duration method is used to calculate the maximum storage volume for a detention facility. The critical storm duration is the storm duration that generates the greatest runoff volume and, therefore, requires the most storage. This volume can be approximated using the following equation:

$$V = \left[Q_i T_d + \frac{Q_i t_c}{4} - \frac{q_o T_d}{2} - \frac{3 q_o t_c}{4}\right] 60$$

Where:

V = Required storage volume, ft^3

Q_i = Inflow peak discharge, cfs, for the critical storm duration, T_d

T_c = Time of concentration, min.

q_o = Allowable peak outflow, cfs

T_d = Critical storm duration, min.

NOTE: The time of concentration should be calculated using one of the methods previously described in this module or another accepted methodology. The allowable peak outflow should be calculated based on the applicable water quantity technical criteria requirement, such as the energy balance equation, channel protection, and/or flood protection.

The equation for the critical storm duration, from the VDOT Drainage Manual, Chapter 6, is shown below:

$$T_d = \sqrt{\frac{2CAa\left(b - \frac{t_c}{4}\right)}{q_o}} - b$$

Where:
T_d = Critical storm duration, min.
C = Runoff coefficient
A = Drainage area, ac.
a & b = Rainfall constants developed for storms of various recurrence intervals and various geographic locations
t_c = Time of concentration, min.
q_o = Allowable peak outflow, cfs

*The a & b rainfall constants are not to be used for any other purpose.

NOTE: The a & b rainfall constants for the 2-, 10-, and 100- year storm recurrence intervals for each county and/or city are included in Chapter 6 of the VDOT Drainage Manual, Appendix 6K-2 https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/technical-guidance-documents/location-and-design/migrated/drainagemanual/DrainManual_Chapter6_acc10272023_PM.pdf.

Reminder: Due to the limitations of the modified rational and rational methods, these methods are not well suited for compliance with the VESM regulatory technical criteria requirements and, as such, should only be used for sizing of pipes and culverts or preliminary sizing of storage facilities.

Notes

Module 9 Problems

TIME OF CONCENTRATION

1. What is the travel time, T (minutes), for a Length, L (feet) = 100 feet, over an average grass surface, with a 4% slope? Use the Seelye Chart (reprinted here on page 81, from VSWHB Appendix A, Section A.3.2.3 Travel Time (Velocity) Method, Figure A-4).

2. For shallow concentrated flow over pavement for 500 feet (L) and 2% slope, what is the travel time, T (minutes)? Use the chart for estimating shallow concentrated flow velocities (reprinted here on page 82, from NEH,2010).

3. Given a channel with a hydraulic radius of 2.0, a slope equaling 0.5%, and a Manning's Roughness Coefficient, n= 0.02, what is the travel time, T (minutes), of flow through a channel over a length of 1,000 feet? Use the Nomograph for Solution of Manning Equation (reprinted here on page 83, from VDOT).

4. What is the total Time of Concentration for the three flow types in questions 1 to 3 above?

RATIONAL FORMULA

$$Q = C \times i \times A$$

Where:

Q (cubic feet/second), Peak Rate of Runoff, is calculated from above equation.

C, Runoff Coefficient, is found from VDOT, Appendix 6E-2

T (minutes), Time of Concentration, is calculated for:

overland flow (Seelye Chart reproduced on page 81)
shallow concentrated (NEH Average Velocity Graph reproduced on page 82)
channel flow (Kirpich Method, VDOT Appendix 6E-5 reproduced on page 84)

i, (inches/hour), Average Rainfall Intensity for design storm frequency of interest (1-year, 2-year, 10-year), from NOAA-Atlas 14

A (acres), Drainage Area, determined from USGS maps or topographic survey

1 acre = 43,560 square feet

5. For a Lynchburg commercial development of 25 acres, with 250,000 square feet of roof top, with 10 acres of asphalt paving for streets and parking, 4 acres of forest with a 4% slope, and with the remainder in lawn with slopes greater than 7%, what is the weighted average runoff coefficient?

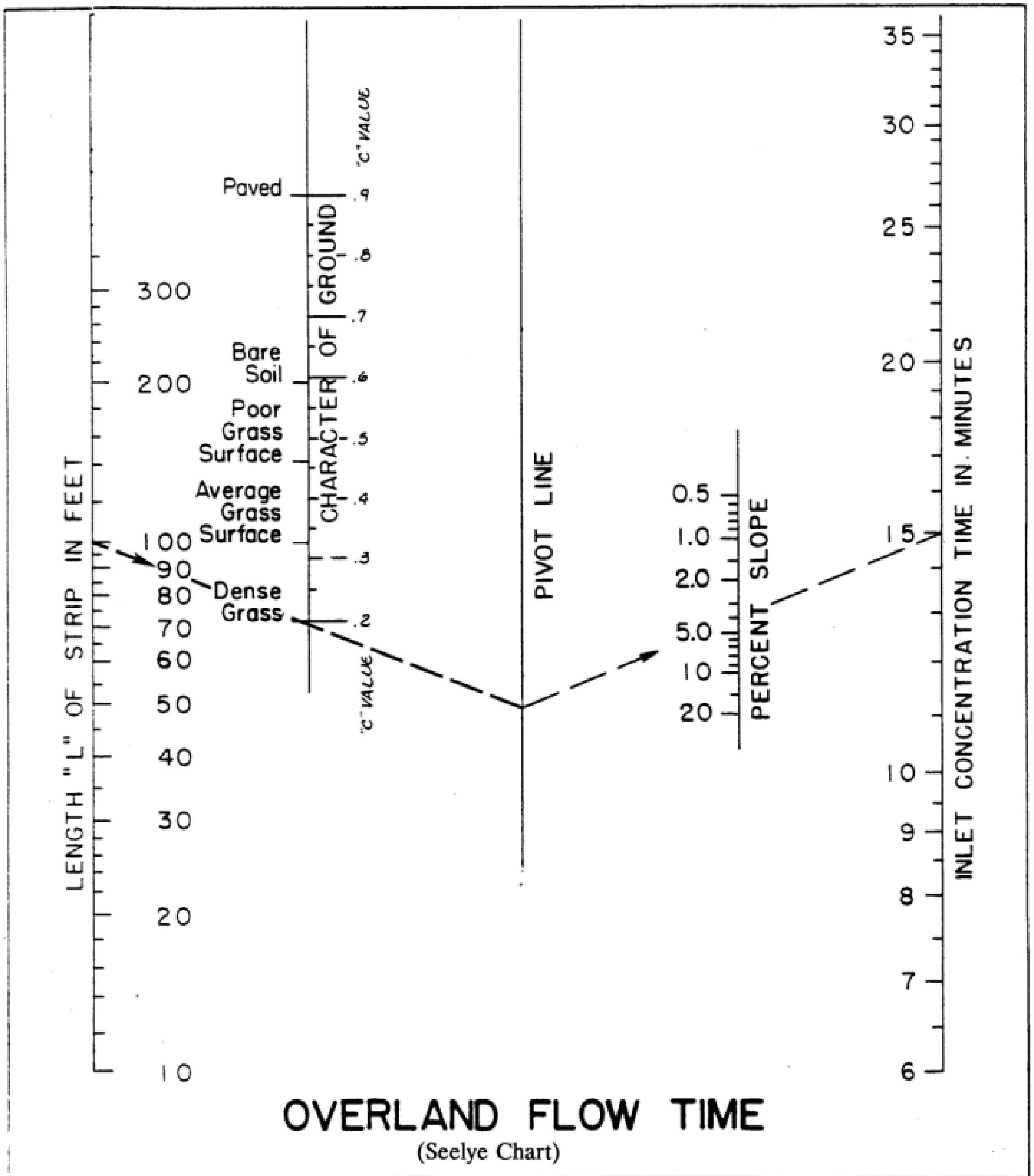
   Use VDOT, Chapter 6, Appendix 6E-2 (reprinted here on page 85)

Land use:	Runoff Coefficient	x	Area(acres)	=	C x A
Roof		x		=	
Asphalt Paving		x		=	
Forest		x		=	
Lawn		x		=	
				Total C x A =	

   C, Weighted Average Runoff Coefficient = Total C x A / Total A (acres)

6. Given a total time of concentration of 20 minutes for the same development, what is the peak rate of runoff from a 10-year storm? Use the IDF chart for the City of Lynchburg provided on page 86.

$$\boldsymbol{Q} = \boldsymbol{C} \times \boldsymbol{i} \times \boldsymbol{A}$$

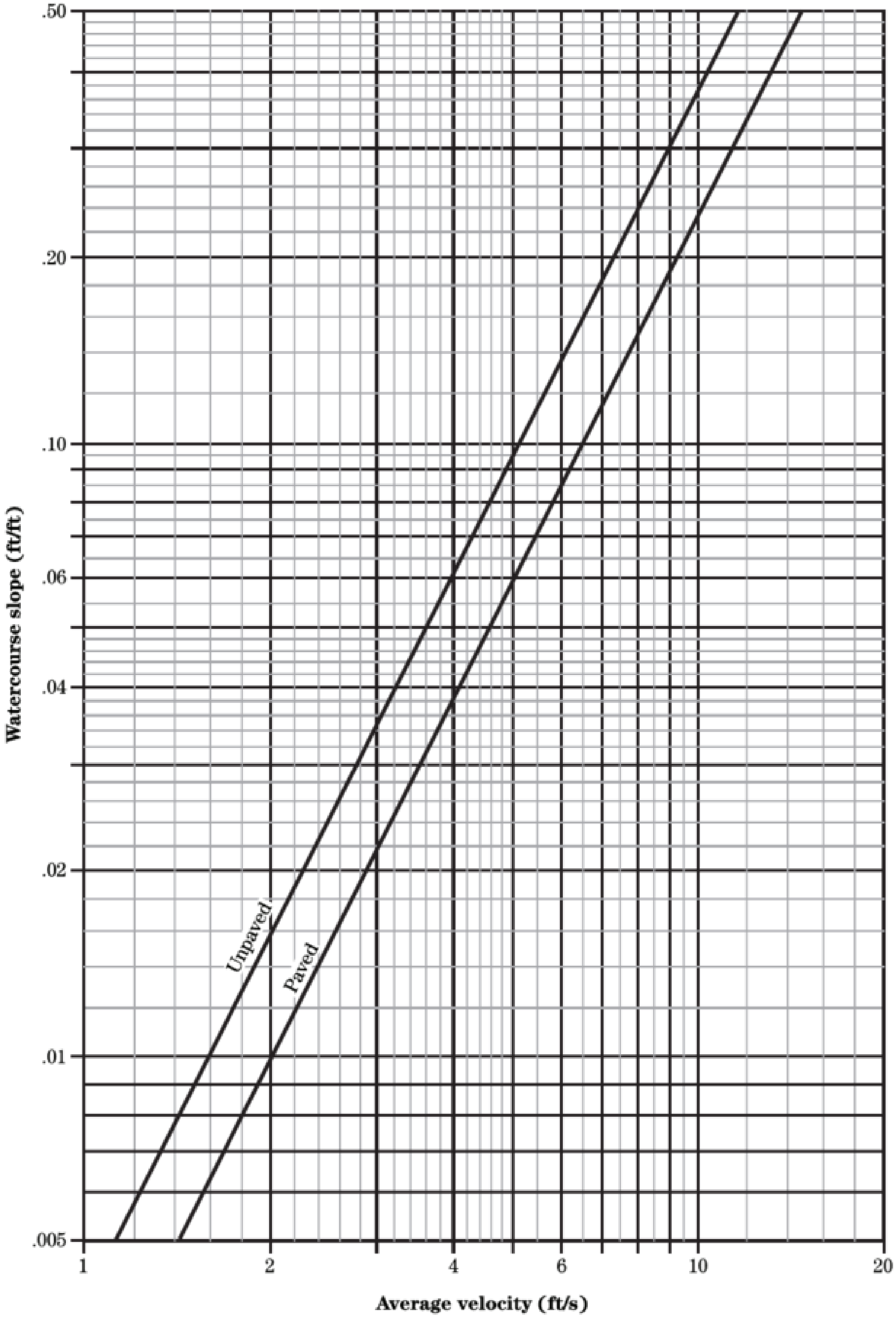


OVERLAND FLOW TIME
(Seelye Chart)

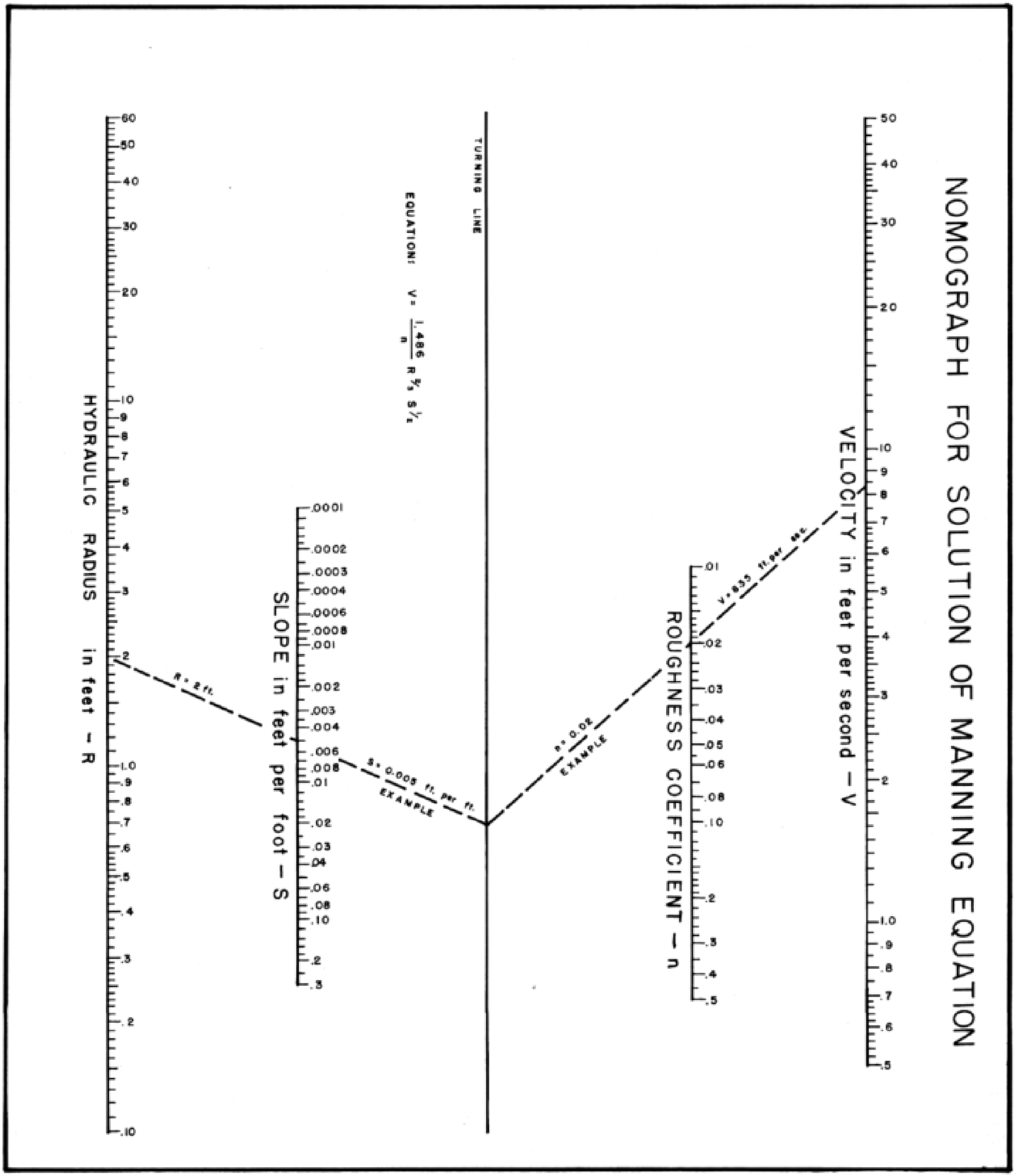
Source: *Data Book for Civil Engineers*, E.E. Seelye

Reference: VSWHB, Appendix A, Section A.3.2.3 Travel Time (Velocity) Method, Figure A-4A

Average Velocities for Estimating Travel Time for Shallow Concentrated Flow



Reference: NEH, 2010

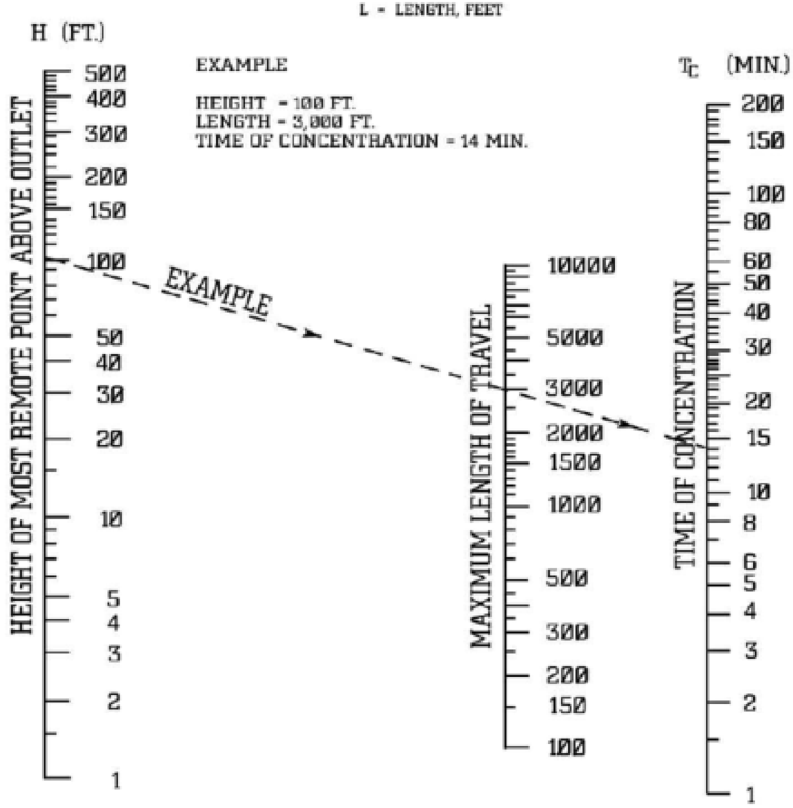

NOMOGRAPH FOR SOLUTION OF MANNING EQUATION
VELOCITY in feet per second – V
ROUGHNESS COEFFICIENT – n
TURNING LINE
EQUATION: V = 1.486/n R^2/3 S^1/2
SLOPE in feet per foot – S
HYDRAULIC RADIUS in feet – R
V = 8.35 ft. per sec.
n = 0.02
EXAMPLE
S = 0.005 ft. per ft.
EXAMPLE
R = 2 ft.

Source: VDOT

Appendix 6D-5 **Time of Concentration for Small Drainage Basins - Kirpich**

$$T_C = 0.00948\ H^{-0.38}\ L^{1.13}$$

T_C - FLOW TIME, MINUTES
H = HEIGHT, FEET
L = LENGTH, FEET



Based on study by P.Z. Kirpich,
Civil Engineering, Vol. 10 No. 6, June 1940, p. 362

TIME OF CONCENTRATION OF SMALL DRAINAGE BASINS

* NOTE:
USE NOMOGRAPH FOR NATURAL BASINS WITH WELL-DEFINED CHANNELS AND FOR MOWED GRASS ROADSIDE CHANNELS.

Comments:
VDOT derived an equation from and added it to this nomograph. This was done without the author's permission in the interest of providing the user with an optional mathematical solution. The Department warrants neither the accuracy nor the validity of this equation and cautions the user that it be used at their own risk.

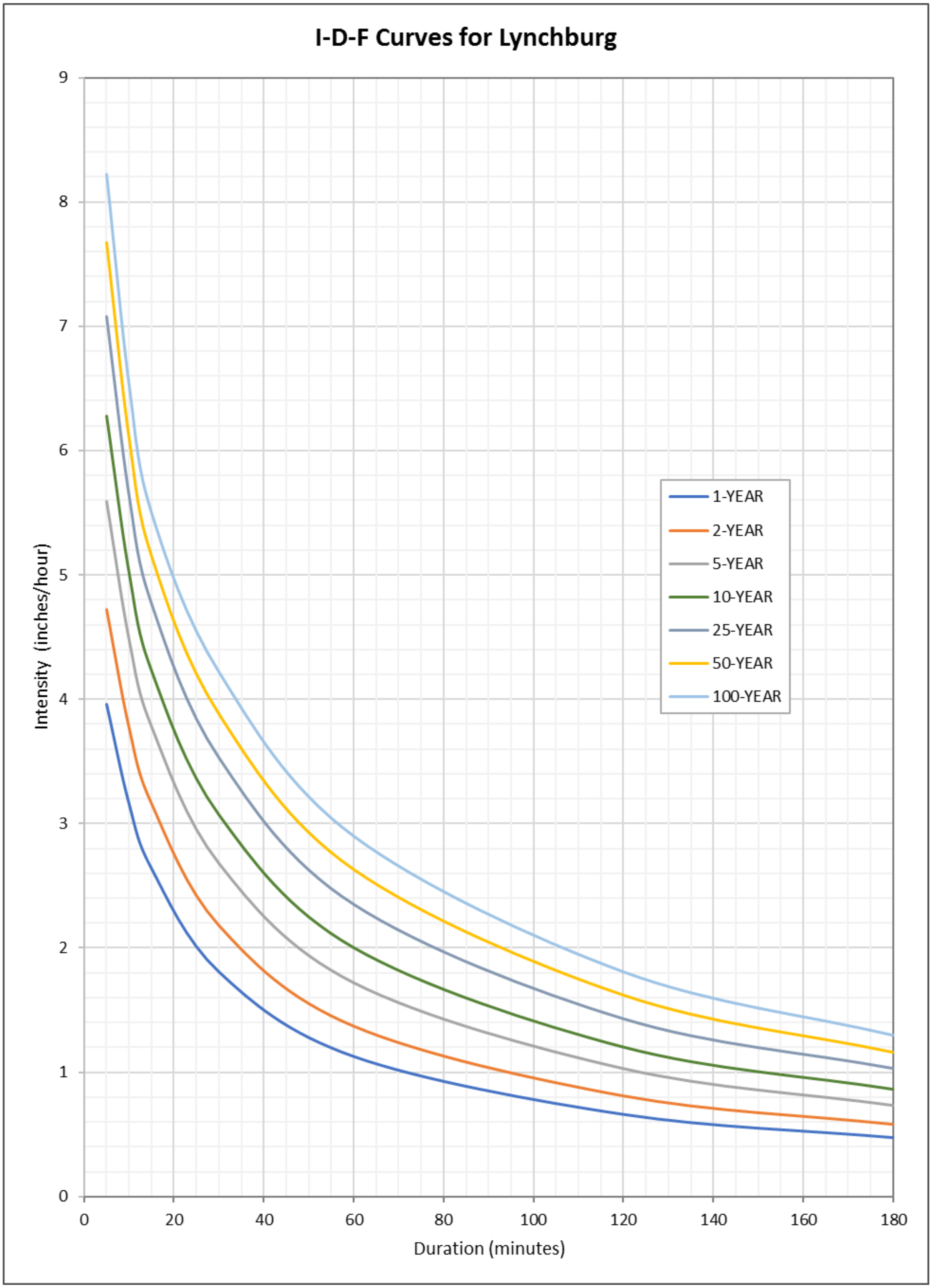
****The Kirpich Chart should only be used for channel time in Virginia.**

Source: VDOT, Appendix 6D-5

Rational Method Coefficients

C_{Cf} Values for 10 Year Storm Frequency (C_f=1.0)					
Land Use		**Average Watershed Slope**			**Average % Impervious**
		Flat <2%	**Rolling 2% - 6%**	**Steep >6%**	
Business, Commercial & Industrial		0.8	0.85	0.90	90%
Apartments and Townhomes		0.65	0.70	0.75	75%
Schools		0.50	0.55	0.60	50%
Residential	lots 10,000 sq. ft	0.40	0.45	0.50	35%
	lots 12,000 sq. ft.	0.40	0.43	0.45	30%
	lots 17,000 sq. ft.	0.35	0.40	0.45	25%
	lots ½ acre or more	0.30	0.35	0.40	20%
Parks, Cemeteries and Unimproved Areas		0.20	0.28	0.35	15%
Paved and Roof Areas			0.90		100%
Cultivated Areas		0.50	0.60	0.70	Varies
Pasture		0.35	0.40	0.45	Varies
Lawns		0.25	0.30	0.35	Varies
Forest		0.20	0.25	0.30	Varies
Railroad Yard Areas		0.20	0.30	0.40	
Roadway Slopes (2:1) w/ Little or No Vegetated Cover			0.70		
Roadway Shoulder & Ditch Areas w/ Little or No Vegetated Cover			0.50		
Roadway Slopes (2:1) w/ Established Vegetated Cover			0.40		
Roadway Shoulder & Ditch Areas w/ Established Vegetated Cover			0.35		

Reference: VDOT Drainage Manual, Chapter 6, Appendix 6E-2



Reference: NOAA Atlas 14 Point Precipitation Frequency Estimates