# Module 10: Hydrology for Plan Reviewers


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Objectives

- 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 Methods

## 10a. Hydrology and Stormwater Engineering Concepts

| Plans approved after July 1, 2014 (except if grandfathered) LDA*: | Water Quantity Part II B Energy Balance + Flooding | Water Quality Part II B Runoff Reduction, Pollutant Removal |
|---|---|---|
| ≥ 1 acre | ✓ | ✓ |
| ≥ 10,000 ft.$^2$ | ✓ | |
| ≥ 2,500 ft.$^2$ in CBPA | ✓ | ✓ |

*May be more stringent (district or locality)

### Plan Reviewer for Stormwater Management

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

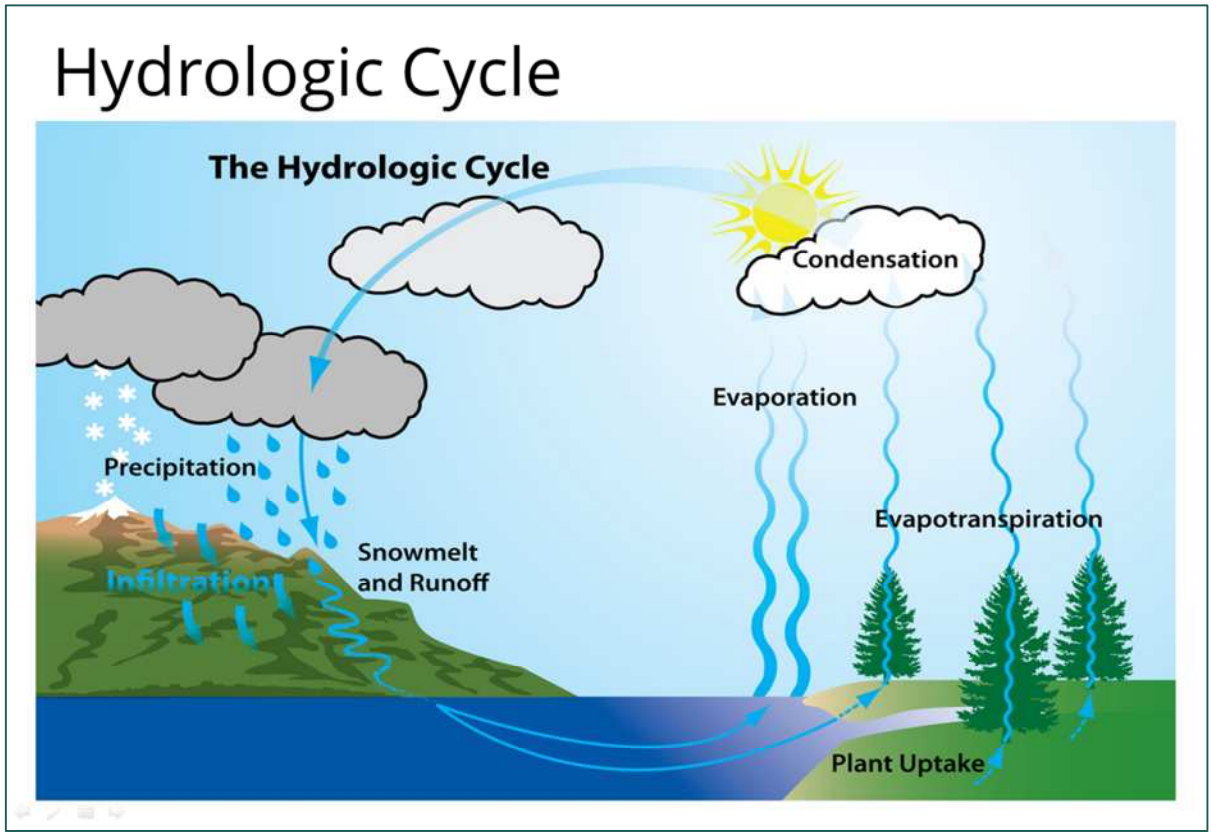
# ESC vs SWM

## Plan Reviewer for Stormwater Management

| Water Quantity | Water Quality | Natural Processes |
|---|---|---|
| • Channel/Flood Protection *(9VAC25-870-66)*<br>• Discharge<br>• Volume<br>• Duration | • Runoff Reduction Method *(9VAC25-870-63)*<br>• Concentration<br>• Volume<br>• Load ( mg/L * $ft^3$) | • Land Cover Types/Soils<br>• Minimize impacts<br>• Mimic (ESD)<br>• Using Runoff Reduction Method |

## Plan Reviewer for Erosion & Sediment Control

| Water Quantity | | Natural Processes |
|---|---|---|
| **MS19: Channel/Flood Protection *(9VAC25-870-66)***<br>Discharge<br>Volume<br>Duration | Energy Balance Equation<br>Localized Flooding?<br>Analyze to Limits of Analysis | • Land Cover Types/Soils<br>• Minimize impacts<br>• Mimic (ESD)<br>• Using Runoff Reduction Method |




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. The elements of the hydrologic cycle that will be discussed in this Module are the statistical rainfall patterns and the response characteristics of the natural and developed landscapes. 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. Many of these assumptions have been 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 Stormwater Management Program (VSMP) regulations (9VAC25-870) attempt to address these stormwater impacts by adopting the Virginia Runoff Reduction Method (VRRM). Using this method, the preferred compliance approach now 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, Environmental 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 II B 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. It is also important to remember that runoff volume reduction is also linked with the revised channel and flood protection criteria in the VSMP regulations (9VAC25-870-66) that now apply to all projects subject to the Erosion and Sediment Control regulations (9VAC25-840) and to land disturbing activities greater than or equal to 2,500 square feet in the Chesapeake Bay Preservation Areas.

There is still a need to model the peak discharge and hydrologic and hydraulic response characteristics of the developed watershed. However, the hierarchy of treatment objectives to achieve the runoff water quality requirements starts with runoff volume reduction.

Part II B of the VSMP regulations (9VAC25-870-66 F) state that predevelopment and postdevelopment runoff characteristics and site hydrology must be verified by:

- Site inspections
- Topographic surveys
- Available soil mapping or studies, and
- Calculations consistent with good engineering practices

This section of the regulation further provides that guidance provided in the Virginia Stormwater Management Handbook (VSMH) and on the Virginia Stormwater BMP Clearinghouse Website (for post-construction BMPs) shall be considered appropriate practices.

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

- Design storms are the **1-, 2-, and 10-year 24-hour storms**.

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

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

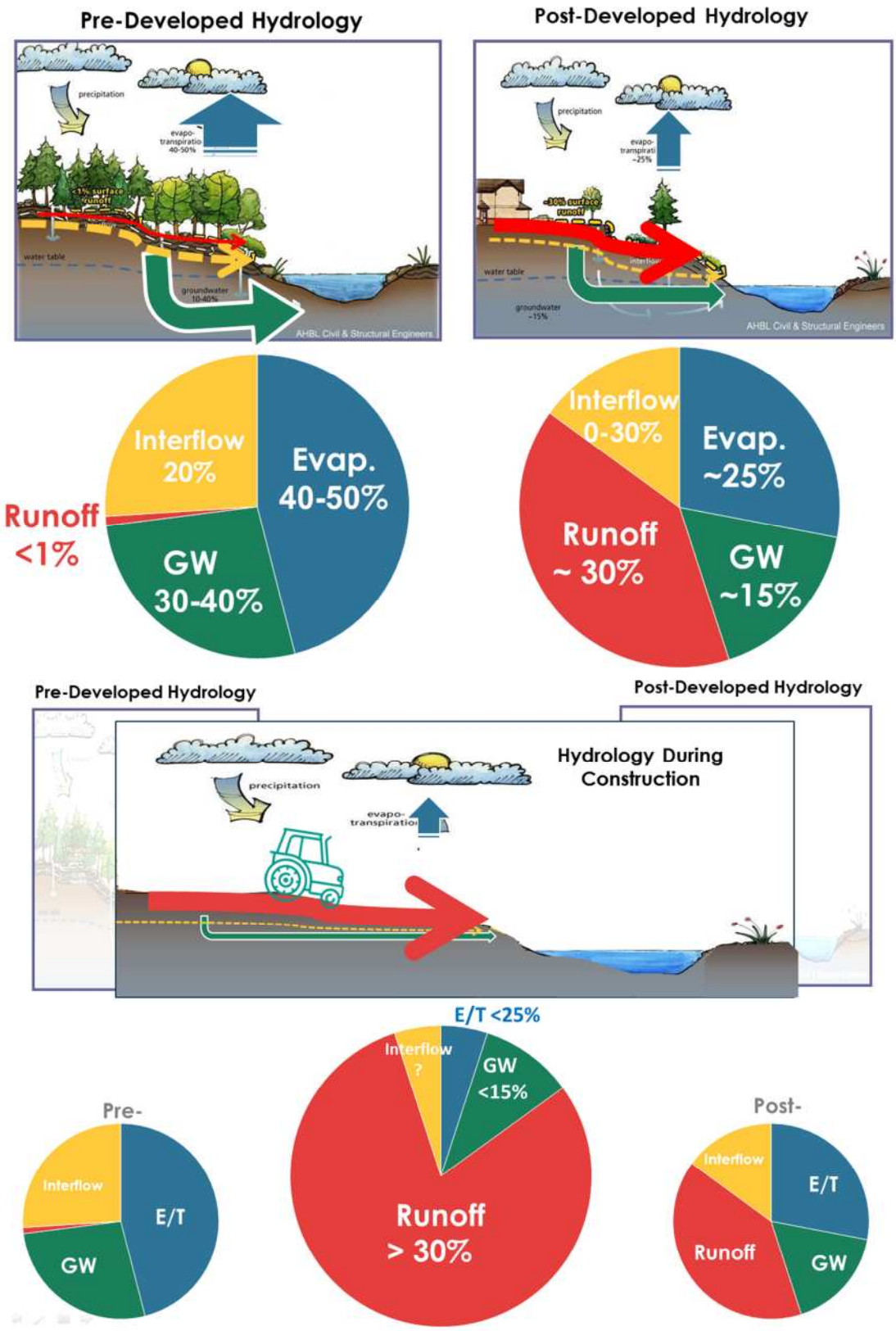
- Determination of flooding and channel erosion impacts to receiving streams due to land-disturbing activities shall be measured at each point of discharge from the land disturbance and such determination ***shall include any runoff from the balance of the watershed that also contributes to that point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

***shall reflect the ultimate land disturbance and shall be used in all engineering calculations***.

The 1992 Virginia Erosion and Sediment Control Handbook (VESCH) provides guidance for compliance reviews of post-construction discharges (as they relate to Minimum Standard 19 prior to July 1, 2014), including recommended stormwater engineering practices. With the promulgation of the VSMP regulations, most of MS-19 has been supplanted by the Part II B stormwater quantity criteria, 9VAC25-870-66. Hydrologic methods, design storms, and good engineering practices must now be consistent with those listed in the stormwater regulation (9VAC25-870-66 F) and the VSMH, as listed above.

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 VSMP regulations. Chapters 4 and 5 of the 1999 VSMH, and NRCS' Technical Release 55 (TR-55): Urban Hydrology for Small Watersheds, can also serve as important resources for plan reviewers.

## 10b. Changes in the Hydrologic Cycle



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

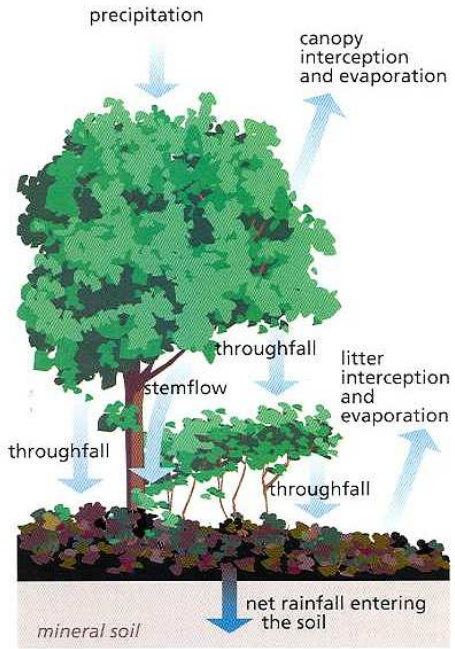
- Reduced evapotranspiration, interception, and infiltration from the loss of vegetation;
- Reduced infiltration from the removal of topsoil and compaction of subsoil;
- Reduced groundwater recharge and stream base flows from increased stormwater runoff over impervious surfaces;
- Reduced infiltration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

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

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

## Reduced evapotranspiration and infiltration from loss of vegetation

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



The benefits of tree canopy for stormwater management

Turf grass, which has commonly been used to replace natural vegetation, produces more runoff than natural open space and forestland, often because it is laid over compacted soil. As discussed earlier in this Participant Guide, the clearing of vegetation and disturbance of land associated with construction activities also lead to increased runoff which, unchecked, can cause erosion, sedimentation, and flooding to downstream properties and natural resources.

*NOTE:*

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

## Reduced infiltration from removal of topsoil and compaction of subsoil

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

## Reduced groundwater recharge and reduced stream base flows

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

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

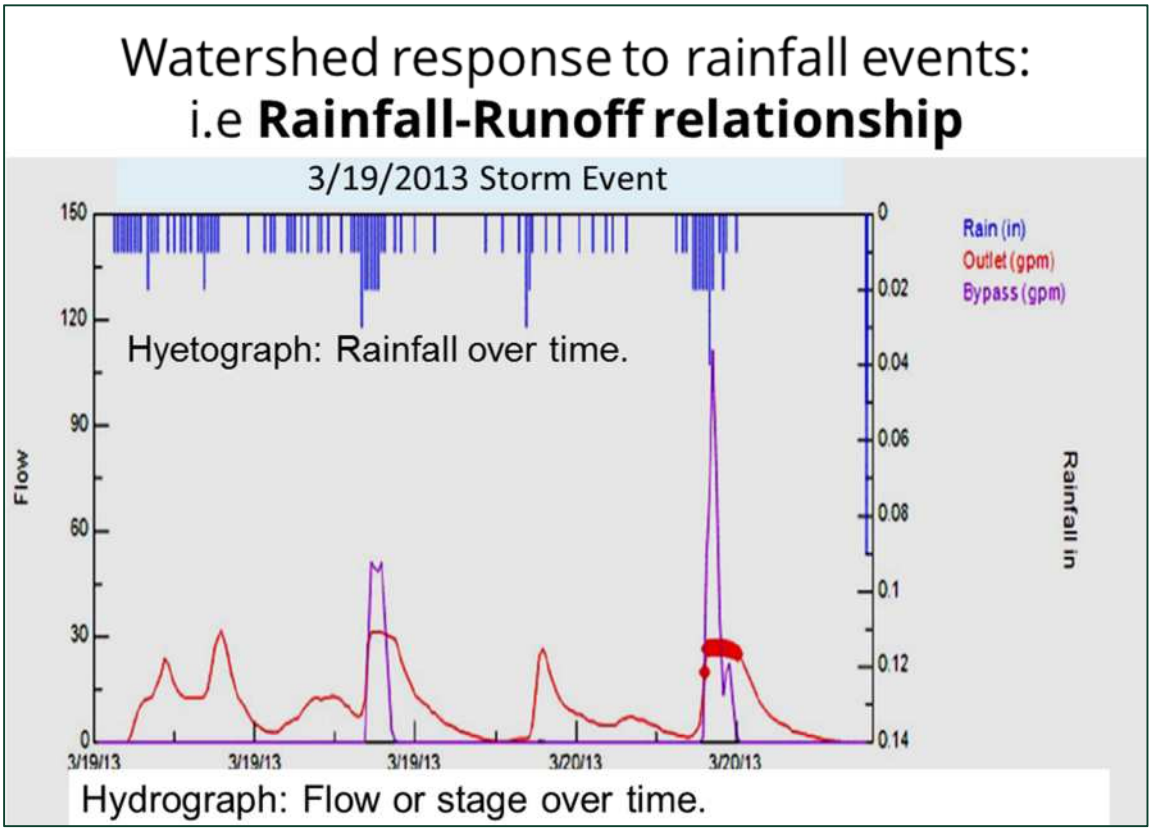
## Reduced infiltration from built or traditional drainage systems

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

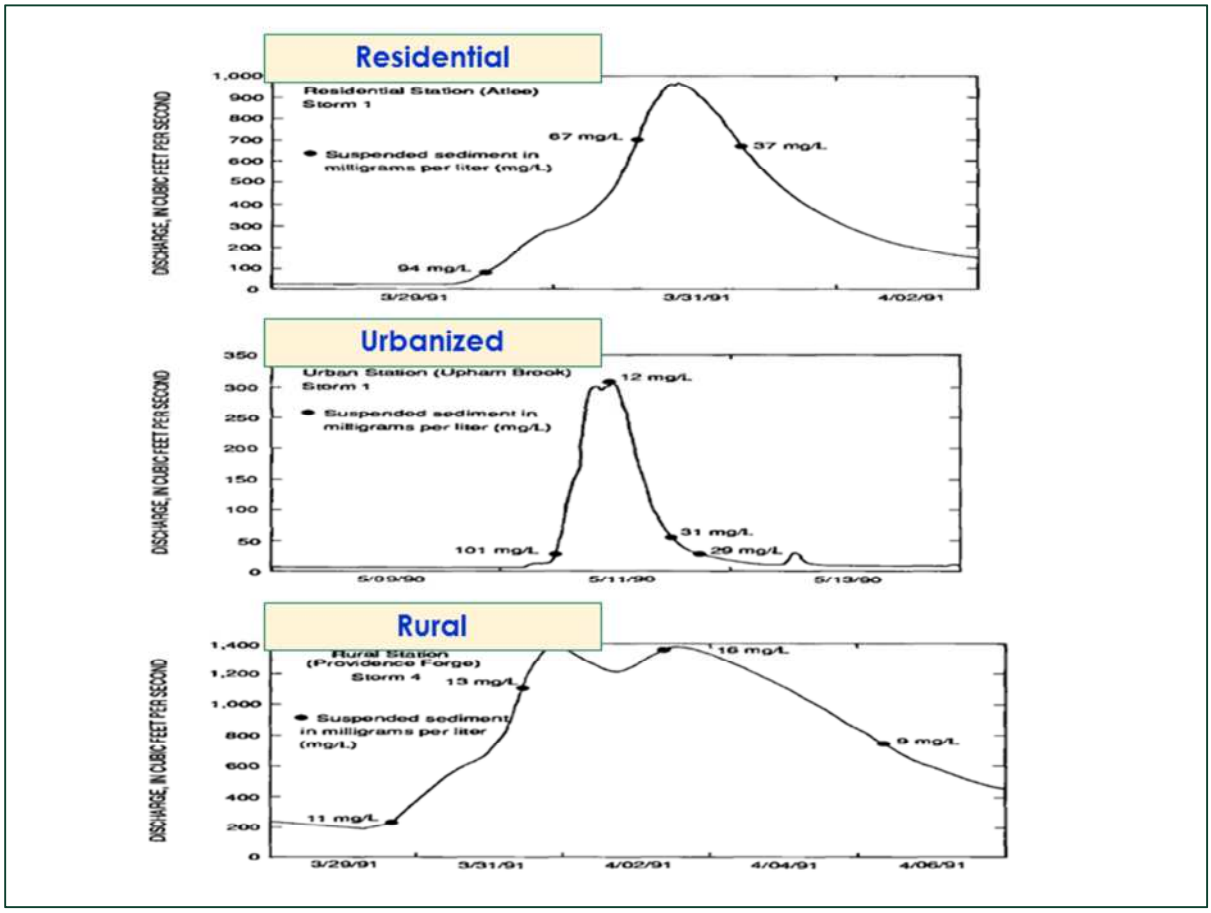
## 10c. Understanding the Water Quantity Requirements

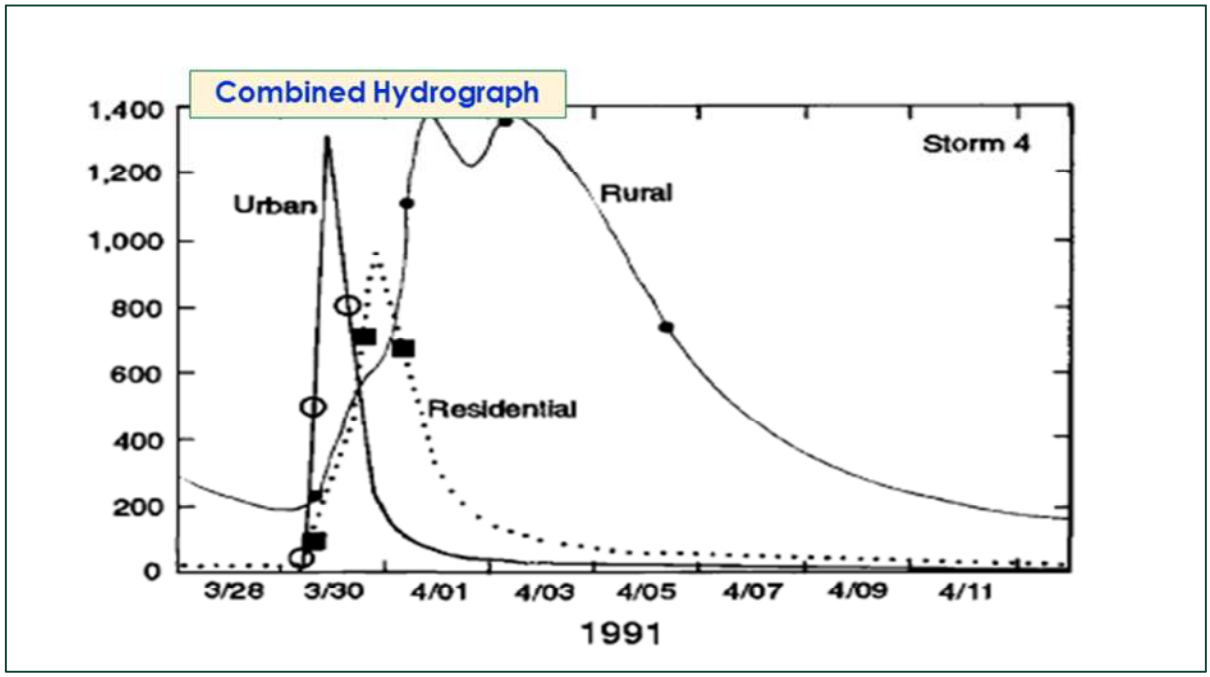
### 10c1. Rainfall-Runoff Relationships

A runoff hydrograph is a graphical plot of the runoff or discharge from a watershed with respect to time. Runoff occurring in a watershed flows downstream in various patterns which are influenced by many factors, such as the amount and distribution of the rainfall, rate of snowmelt, stream channel hydraulics, infiltration capacity of the watershed, and others, that are difficult to define. Empirical relationships have been developed to assist in estimating potentially complex hydrographs. The critical element of the analysis, as with any hydrologic analysis, is the accurate description of the watershed's rainfall-runoff relationship, flow paths, and flow times. From this data, runoff hydrographs can be generated.



## Data from Three Different Watersheds



Natural hydrographs can be developed using extensive watershed gauge data. Stream gauge data is very useful for calibrating models or synthetic hydrographs. However, the lack of such data mostly eliminates the option of using a natural hydrograph.

### Estimating Runoff

A synthetic hydrograph is a simulation using watershed parameters and storm characteristics from a large number of watersheds. 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, ground cover, 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 the typical hydrograph for a watershed where the runoff volume under the hydrograph is adjusted to equal 1 inch of equivalent depth over the watershed. Different modeling approaches for runoff estimation build on this concept of the unit hydrograph.

**Rainfall-Runoff Relationships:**

Impossible to collect at every discharge point of interest

Each method limited in specific runoff parameters it can provide

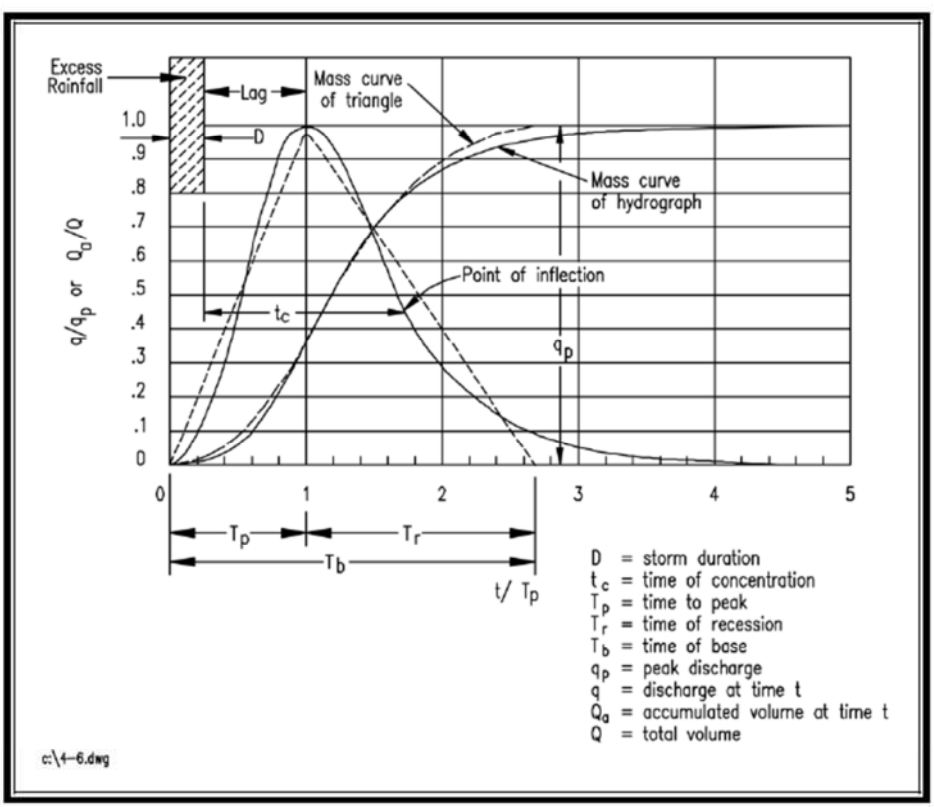
The unit hydrograph is based on the analysis of a single watershed's rainfall-runoff and streamflow data and can be used to better predict response characteristics to various storm events for that specific watershed. This is a useful tool for certain applications such as flood studies of river basins. Generally, however, basic streamflow and runoff data are not available to create a unit hydrograph for most development projects.

Therefore, techniques have been developed that allow for the generation of synthetic unit hydrographs.

The method developed by the Soil Conservation Service (SCS) for constructing synthetic unit hydrographs is based on the dimensionless unit hydrograph. This dimensionless graph is the result of an analysis of a large number of natural unit hydrographs from a wide range of watersheds varying in size and geographic locations. This approach is based on using the watershed peak discharge and time to peak discharge to relate the watershed characteristics to the dimensionless hydrograph features. SCS methodologies provide various empirical equations, as discussed in this module and Module 11, to solve for the peak and time to peak for a given watershed. Various equations are then used to define critical points on the hydrograph and thus define the runoff hydrograph. The following runoff hydrograph (Figure 4-6 from the 1999 VSMH, Volume II) shows the SCS Dimensionless Unit Hydrograph. The critical points are the time to peak, represented by the watershed lag time, and the point of inflection, represented by the time of concentration. The National Engineering Handbook (Section 4; Hydrology, Chapters 15-16), can be referenced for more information on unit hydrographs.

**FIGURE 4 - 6**

***Dimensionless Curvilinear Unit Hydrograph and Equivalent Triangular Hydrograph***




*Source: NEH-4, Chapter 16*

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 which 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.

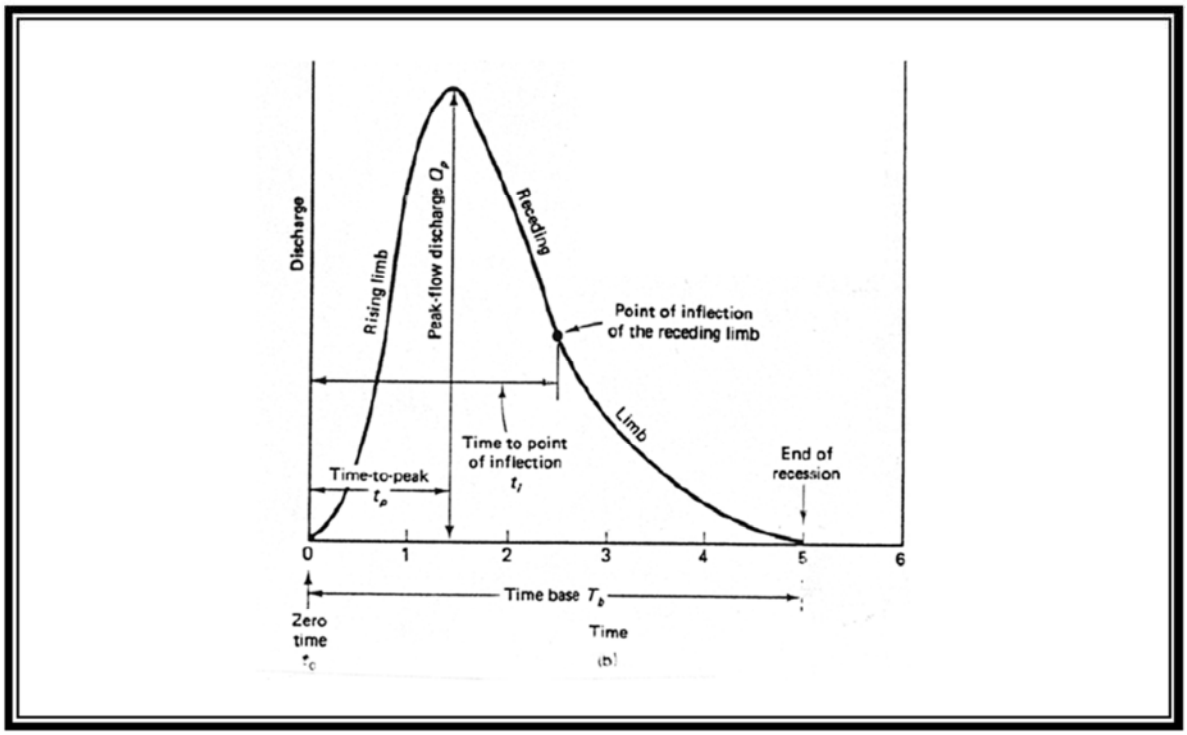
3. **Base flow** occurs when there is a fairly steady flow into a stream channel from natural storage. The flow comes from lakes or swamps, or from an aquifer replenished by infiltrated rainfall or surface runoff.

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. The following figure is a typical hydrograph (a plot of ***discharge*** or ***runoff***) (Figure 4-7 from the 1999 VSMH, Volume II). 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, then a hydrograph is needed. If the purpose of a study is to design a roadway culvert or other

simple drainage improvement, then only the peak rate of flow is needed. Therefore, the purpose of a given study will dictate the methodology which 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***.

***Runoff Hydrograph***




*1999 VA Stormwater Management Handbook Volume II (Figure 4-7)*

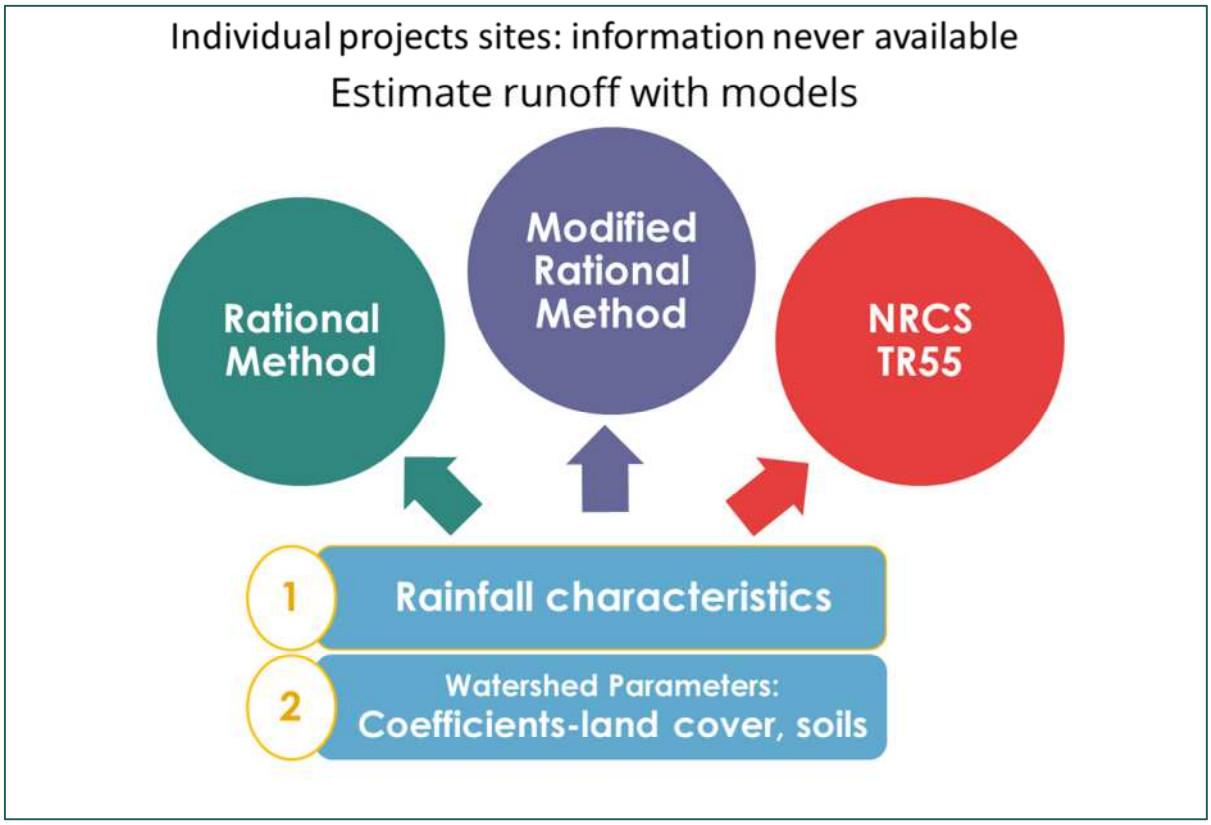
This Rational Method and Modified Rational Method are briefly described in this module and the TR-55 Graphical Method (and mention of the TR-55 Tabular Method) is covered in Module 11. Plan reviewers should be familiar with all of them since they require different types of input and generate different types of results.

Many software programs are available which develop these methodologies, utilizing 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.

Examples provided in Chapter 6 of the 1999 VSMH (Volume II), utilize SCS TR-20 . Other readily available software programs also utilize SCS Methods. The accuracy of the

computer model is based upon the accuracy of the input which is typically generated through the Rational or SCS methodologies. The designer and plan reviewer should be familiar with all of the methods covered here since any one may be appropriate for the specific site or watershed being modeled.

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



## Precipitation

| | |
|---|---|
| 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) |
| Type 2 or 3 | Distribution |

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

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

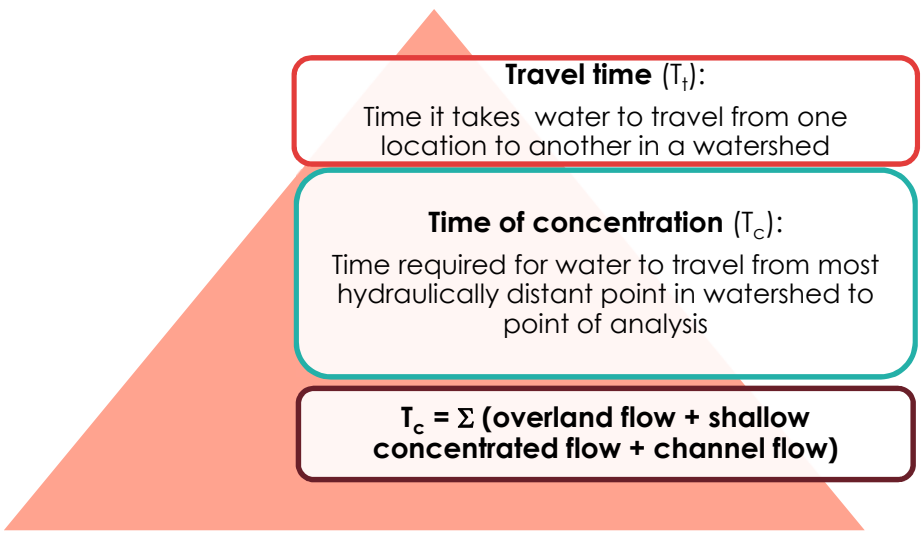
10 year event = 1/10 or o.1 or 10% chance of occurring in any given year

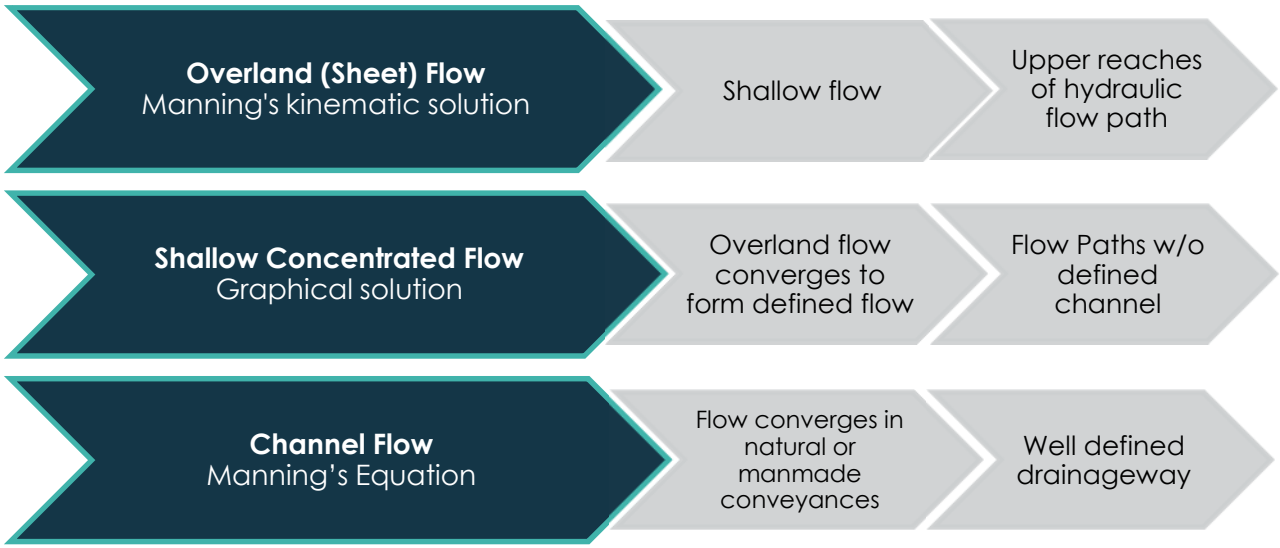
1 year event = 1/1 or 1 or 100% chance of occurring in any given year

## 10c2. Time of Concentration and Travel Time

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

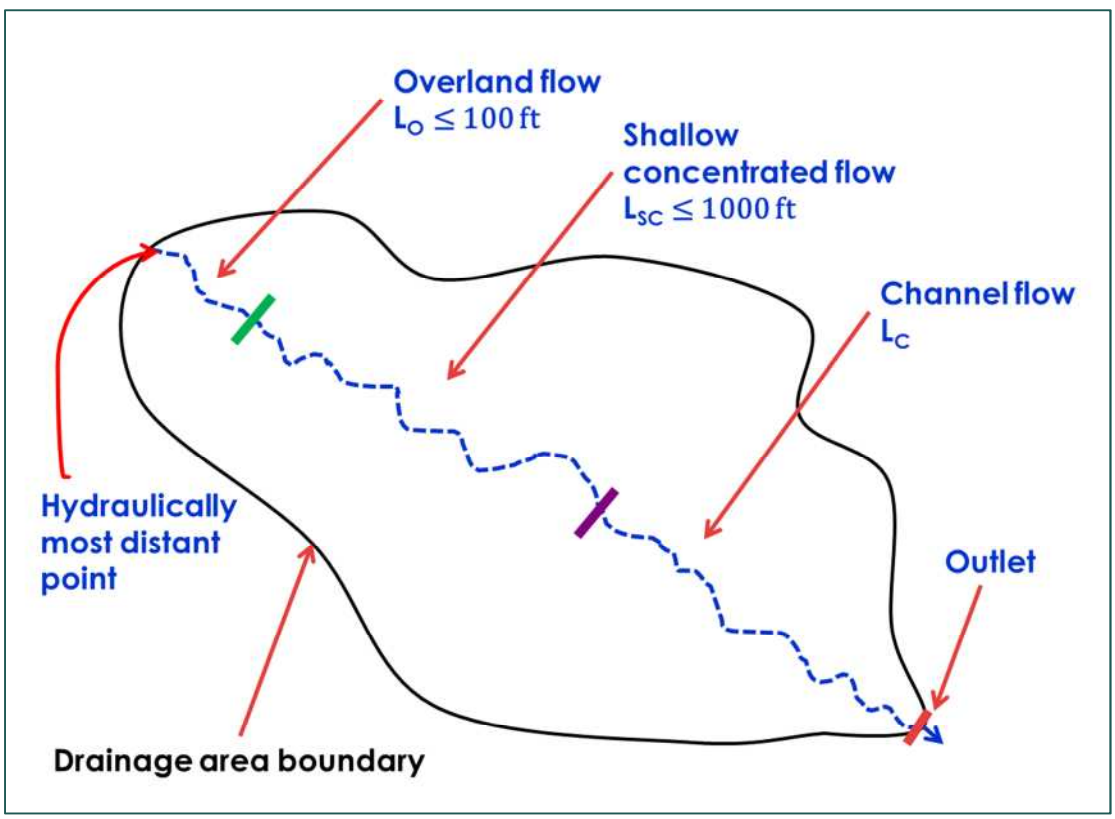
The time of concentration, $T_c$, plays an important role in developing the peak discharge for a watershed and is one of the critical factors in runoff estimation methods. Urbanization usually decreases the $T_c$, which results in an increase in peak discharge. For this reason, to accurately model the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






## Flow Segments (Overland Sheet, Shallow Concentrated and Chanel Flow)

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



### *Overland (Sheet) Flow*

Overland or sheet flow is shallow flow over plane surfaces. For the determination of time of concentration, overland flow usually exists in the upper reaches of the hydraulic flow path.

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 VESCH, can be consulted for more information.

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

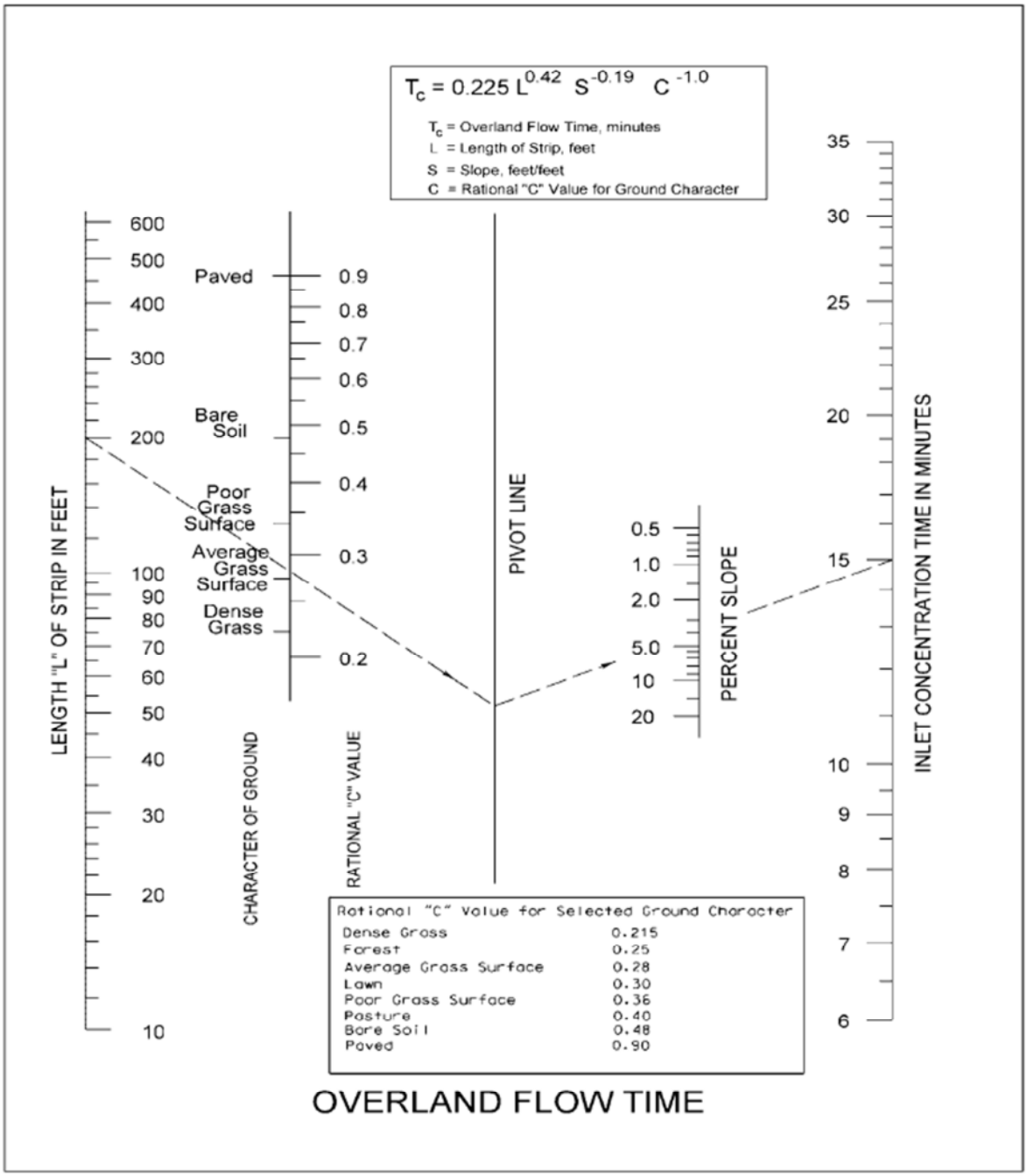
---

*Note: the hydraulic length for overland flow should be determined for each site. Do not assume that the length of overland flow equals the maximum recommended length.*

---

a) **Seelye Method**: Travel time for overland flow can be determined by using the Seelye chart (VESCH, Plate 5-1, p. V-11; presented below). This method is perhaps the simplest and is most commonly used for small developments where a greater margin of error is acceptable.

   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.

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

Comments:
VDOT added a 'C-VALUE' scale and table* and a derived equation for Overland Flow Time to this nomograph. This was done without the permission of the author in the interest of providing the user with a quantitative comparison for the selection of 'CHARACTER OF GROUND' and an optional numerical solution to the nomograph. The Department warrants neither the accuracy nor the validity of either enhancement and cautions the user that it be used at their own risk.

* Rev 9/11

Source: VDOT Drainage Manual, Chapter 6. Also presented in VESCH, Plate 5-1, p. V-11.

b) <u>Kinematic Wave Method:</u> This method allows for the input of rainfall intensity values, thereby providing the specific overland flow travel time for the selected design storm. The equation is:

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

$L$ = length of overland flow (feet)
$n$ = Manning's roughness coefficient (Table 5-3, 1992 VESCH, p. V-30)
$i$ = rainfall intensity (inches/hour) (Plates 5-4 to 5-18, VESCH, p. V-14 to V28)
$S$ = slope (feet/feet)

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.

1. Assume a rainfall intensity value (from Plates 5-4 to 5-18 of the VESCH, p. V-14 to V-28) or use the Seelye chart for an approximate duration value) and solve the equation for travel time ($T_t$).

2. Compare the assumed rainfall intensity value with the rainfall intensity value (from Plates 5-4 to 5-18) that corresponds with the travel time.

3. 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 VESCH for more details).

c) <u>SCS-TR-55 method:</u> [See Module 11 and/or the SCS-TR-55 Manual for more details.]

TR-55 utilizes Manning's kinematic solution to compute $T_c$ for overland sheet flow. The roughness coefficient is the primary culprit in the misapplication of the kinematic $T_c$ equation. Care should be taken to accurately identify the surface conditions for overland flow. Table 3-1 in TR-55 and Table 5-7 in VESCH, p. V-61 provide selected coefficients for various surface conditions. Refer to TR-55 for the use of Manning's Kinematic Equation.

**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)

NOTE:

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

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

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

*The designer should: (1) Select a flow path that is the most hydrologically remote flow path, and (2) Consider the relative homogeneity of the watershed.*

### *Shallow Concentrated Flow*

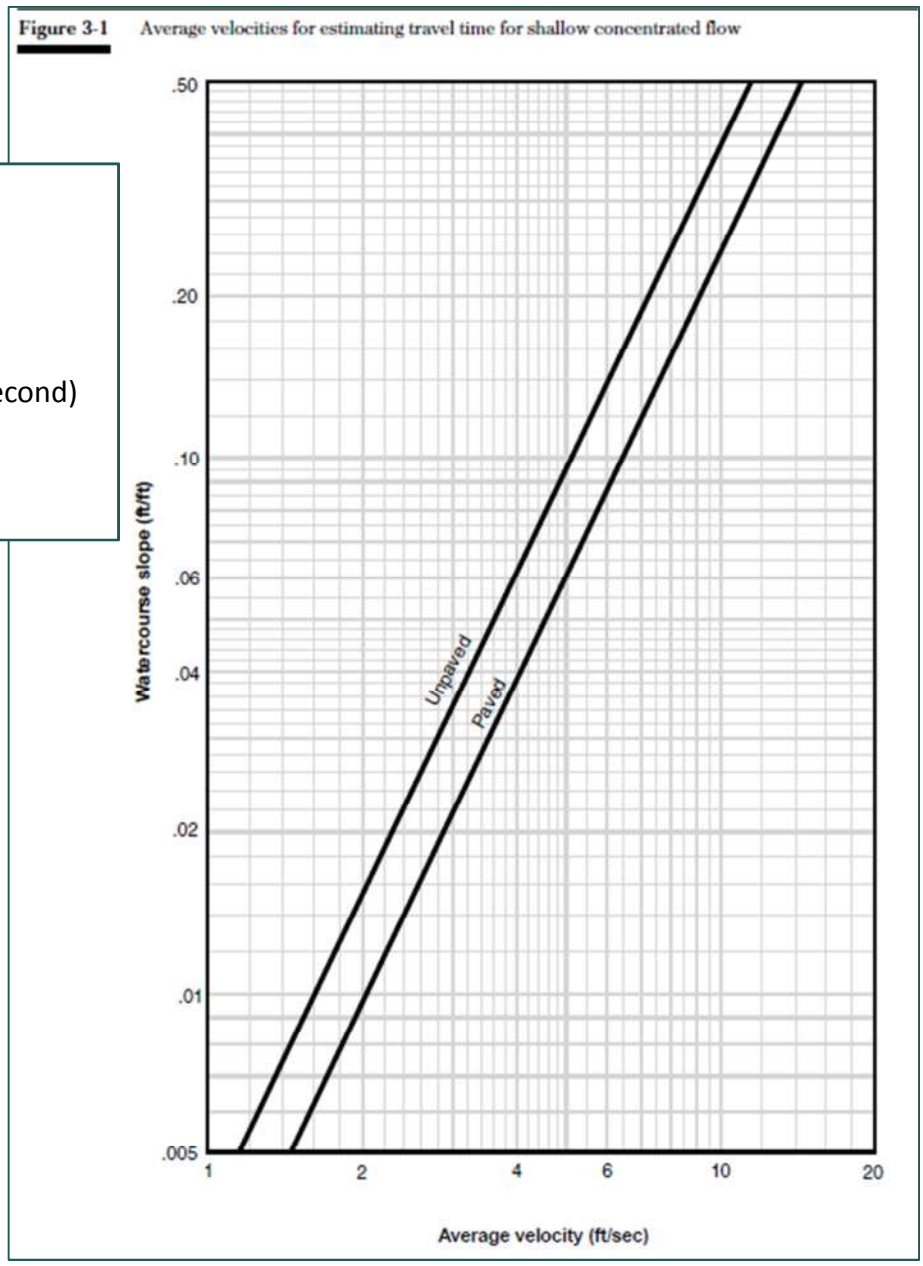
Shallow concentrated flow usually begins where overland flow converges to form defined flow paths, which may include small rills or gullies. Shallow concentrated flow can exist in natural depressional features, small manmade drainage ditches (paved and unpaved) and in curb and gutters. TR-55 provides a graphical solution for shallow concentrated flow. Typically there is not a well-defined channel cross-section. The input information needed to solve for this flow segment is the land slope and the surface condition (paved or unpaved). The average velocity for this flow can be determined using charts similar to the ones presented below from TR-55 and VESCH, Plate 5.2, p. V-12.

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

*L* = flow length (feet)

*V* = average velocity (feet/second)

*t* = conversion factor




Average velocities for estimating travel time for shallow concentrated flow.
Source: VESCH, Plate 5.2, p. V-12; TR-55, Figure 3-1

### *Channel Flow*

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

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

**Manning's Equation**

V = velocity (fps)

n = Manning's roughness coef.

R = hydraulic radius (A/P)

A= wetted cross sectional area

P=wetted perimeter(ft)

**s = slope (ft/ft)**

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

*L* = channel flow length (feet)

*V* = average velocity(feet/second)

*** use Manning's equation***

Worksheet 3 from TR-55 (reproduced below) 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. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute $T_t$ hr | | + | = |

### Shallow concentrated flow

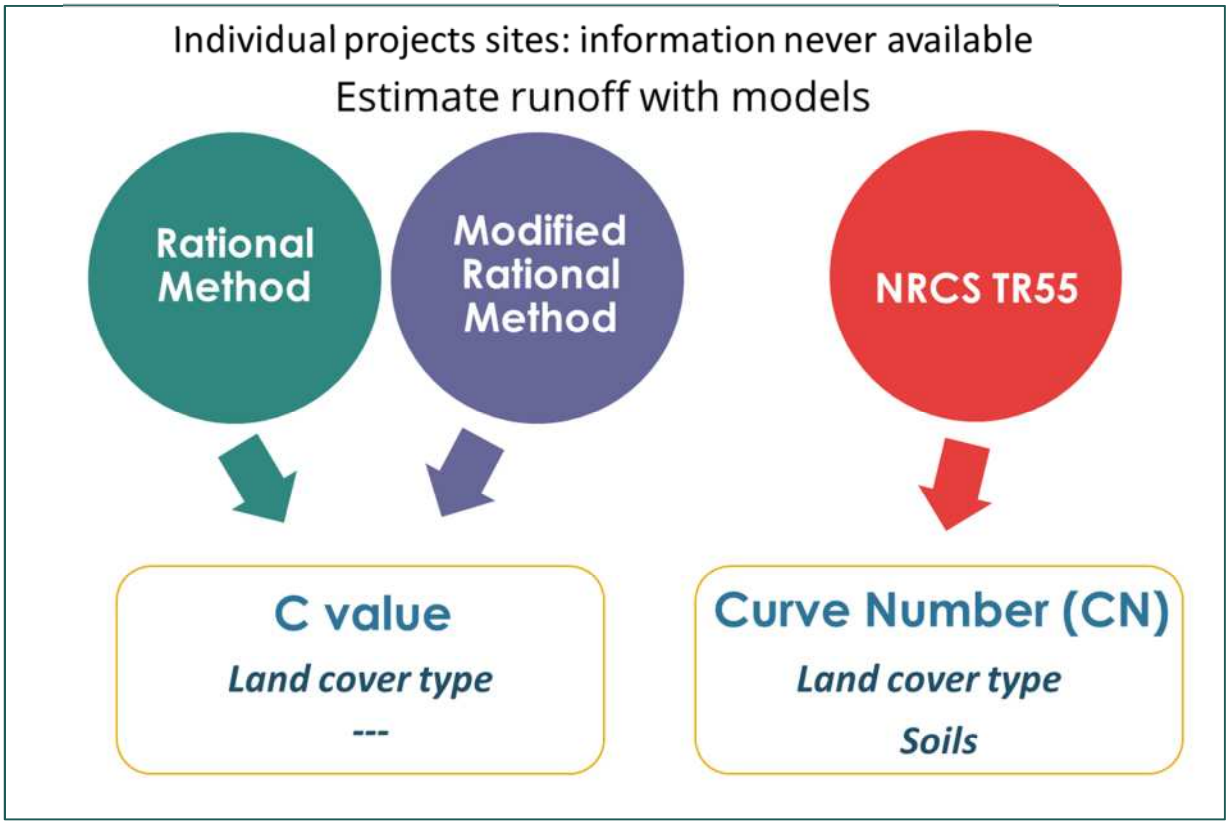
| | Segment ID | | |
|---|---|---|---|
| 7. Surface description (paved or unpaved) | | | |
| 8. Flow length, L ft | | | |
| 9. Watercourse slope, s ft/ft | | | |
| 10. Average velocity, V (figure 3-1) ft/s | | | |
| 11. $T_t = \frac{L}{3600\ V}$ Compute $T_t$ hr | | + | = |

### Channel flow

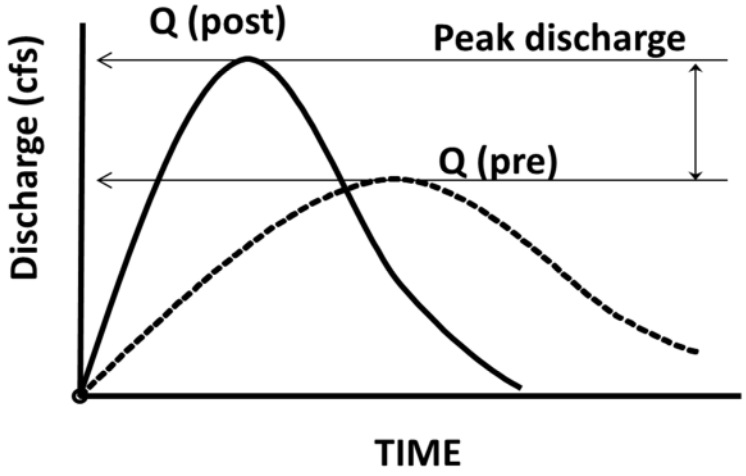
| | Segment ID | | |
|---|---|---|---|
| 12. Cross sectional flow area, a $ft^2$ | | | |
| 13. Wetted perimeter, $p_w$ ft | | | |
| 14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r ft | | | |
| 15 Channel slope, s ft/ft | | | |
| 16. Manning's roughness coefficient, n | | | |
| 17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ft/s | | | |
| 18. Flow length, L ft | | | |
| 19. $T_t = \frac{L}{3600\ V}$ Compute $T_t$ hr | | + | = |
| 20. Watershed or subarea $T_c$ or $T_t$ (add $T_t$ in steps 6, 11, and 19) Hr | | | |

# Rainfall-Runoff Coefficients

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



# Hydrographs




**Graphical representation of discharge over time**

## 10c2. Rational Method

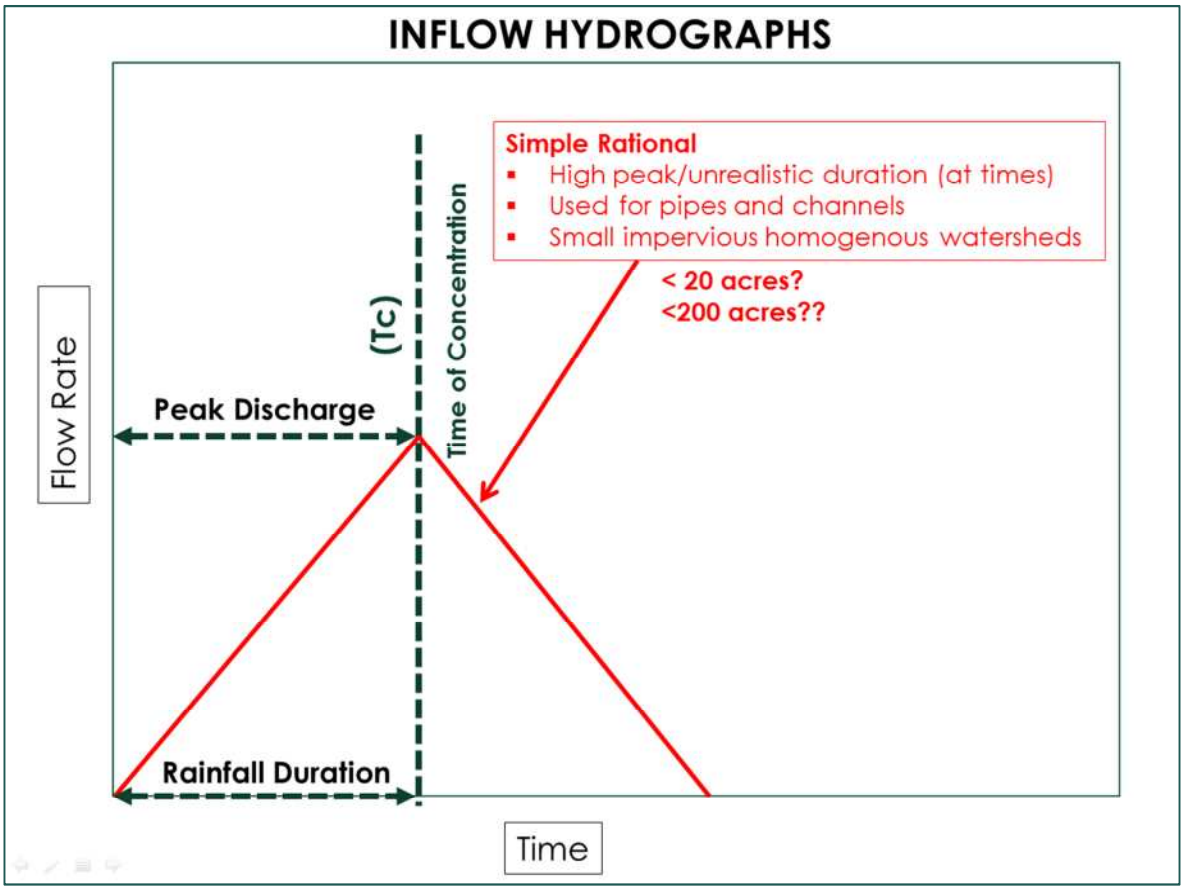
The Rational Method was introduced in 1880 for determining peak discharges from drainage areas. It is frequently criticized for its simplistic approach, but this same simplicity has made the Rational Method one of the most widely used techniques today. The Rational Formula estimates the peak rate of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

The Rational Formula is expressed as follows:

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

**Rational Formula**

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



## 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. Values from the VESCH are presented in Table 10-1. Recommended values for urban land use presented in Table 10-2 are included in the 1999 VSMH, Volume II, and represent adjustments intended to make the rational method more accurate with respect to the integrated effects of drainage basin parameters: *land use*, *soil type*, and *average land slope*.

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

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

Soil properties can change throughout the construction process due to compaction, cut, and fill operations. If these changes are not reflected in the runoff coefficient, the accuracy of the model will decrease. Some localities arbitrarily require an adjustment in the runoff coefficient for pervious surfaces due to the effects of construction on soil infiltration capacities. This is discussed in more detail in Section 4-4.3 of the 1999 VSMH, however, such adjustments are generally not possible using the Rational Method since soil conditions are not considered.

**Table 10-1 Rational Formula Runoff Coefficients**

(Source: VESCH; page V-29, Table 5-2)

**TABLE 5-2**
**VALUES OF RUNOFF COEFFICIENT (C) FOR RATIONAL FORMULA**

| Land Use | C | Land Use | C |
|---|---|---|---|
| Business: | | Lawns: | |
| Downtown areas | 0.70-0.95 | Sandy soil, flat, 2% | 0.05-0.10 |
| Neighborhood areas | 0.50-0.70 | Sandy soil, average, 2-7% | 0.10-0.15 |
| | | Sandy soil, steep, 7% | 0.15-0.20 |
| | | Heavy soil, flat, 2% | 0.13-0.17 |
| | | Heavy soil, average, 2-7% | 0.18-0.22 |
| | | Heavy soil, steep, 7% | 0.25-0.35 |
| Residential: | | Agricultural land: | |
| Single-family areas | 0.30-0.50 | Bare packed soil | |
| Multi units, detached | 0.40-0.60 | * Smooth | 0.30-0.60 |
| Multi units, attached | 0.60-0.75 | * Rough | 0.20-0.50 |
| Suburban | 0.25-0.40 | Cultivated rows | |
| | | * Heavy soil, no crop | 0.30-0.60 |
| | | * Heavy soil, with crop | 0.20-0.50 |
| | | * Sandy soil, no crop | 0.20-0.40 |
| | | * Sandy soil, with crop | 0.10-0.25 |
| | | Pasture | |
| | | * Heavy soil | 0.15-0.45 |
| | | * Sandy soil | 0.05-0.25 |
| | | Woodlands | 0.05-0.25 |
| Industrial: | | Streets: | |
| Light areas | 0.50-0.80 | Asphaltic | 0.70-0.95 |
| Heavy areas | 0.60-0.90 | Concrete | 0.80-0.95 |
| | | Brick | 0.70-0.85 |
| Parks, cemeteries | 0.10-0.25 | Unimproved areas | 0.10-0.30 |
| Playgrounds | 0.20-0.35 | Drives and walks | 0.75-0.85 |
| Railroad yard areas | 0.20-0.40 | Roofs | 0.75-0.95 |

Note: The designer must use judgement to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lowest C values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the highest C values.

**Table 10-2 Rational Formula Runoff Coefficients for Urban Land Use**
(Source: 1999 VSWMH; p. 4-20)

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

## 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 10-1**:

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 :

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

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

$$= 0.39$$

**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:

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

Where $C_f$ values are provided in Table 10-3 below.

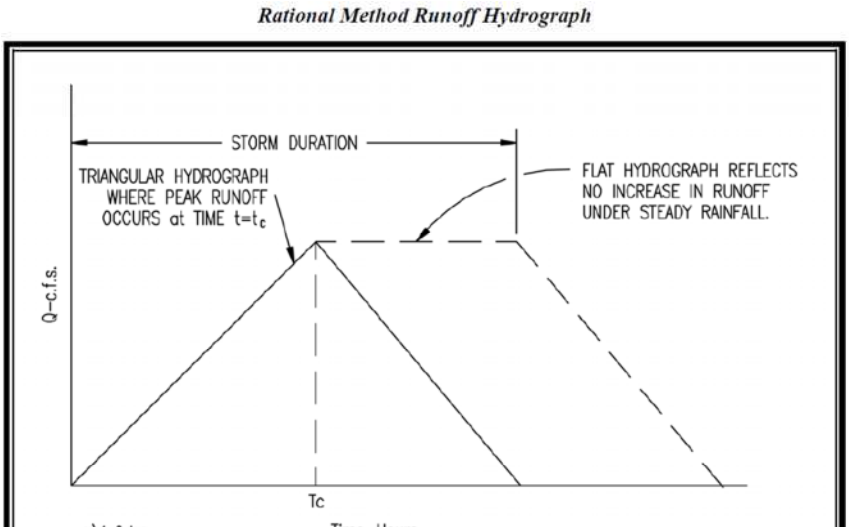
**TABLE 10-3**
**Rational Equation Frequency Factors**
(Source: 1999 VSMHB, Table 4-4)

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

## Time of Concentration ($T_c$) for Rational Method

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

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

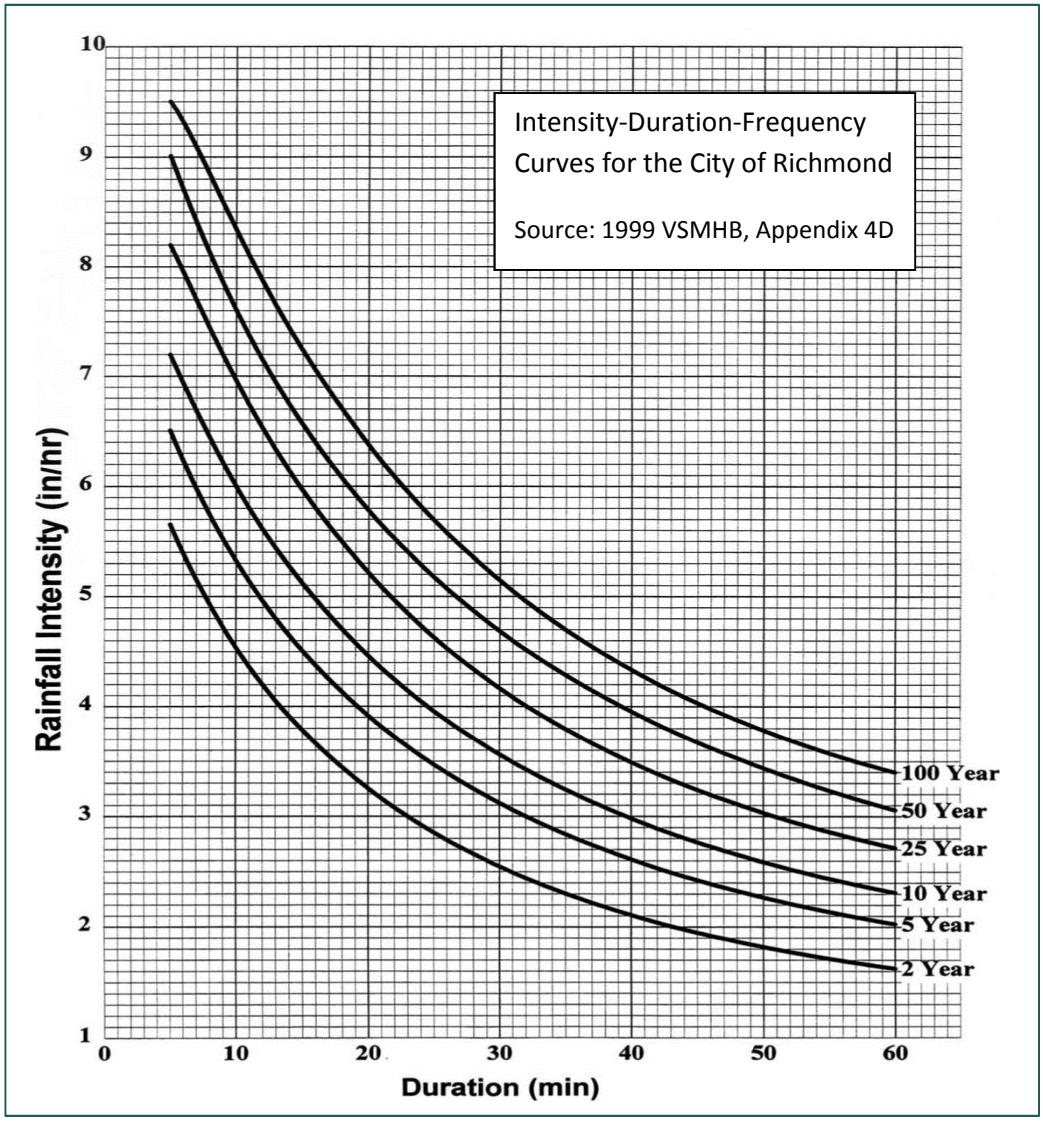


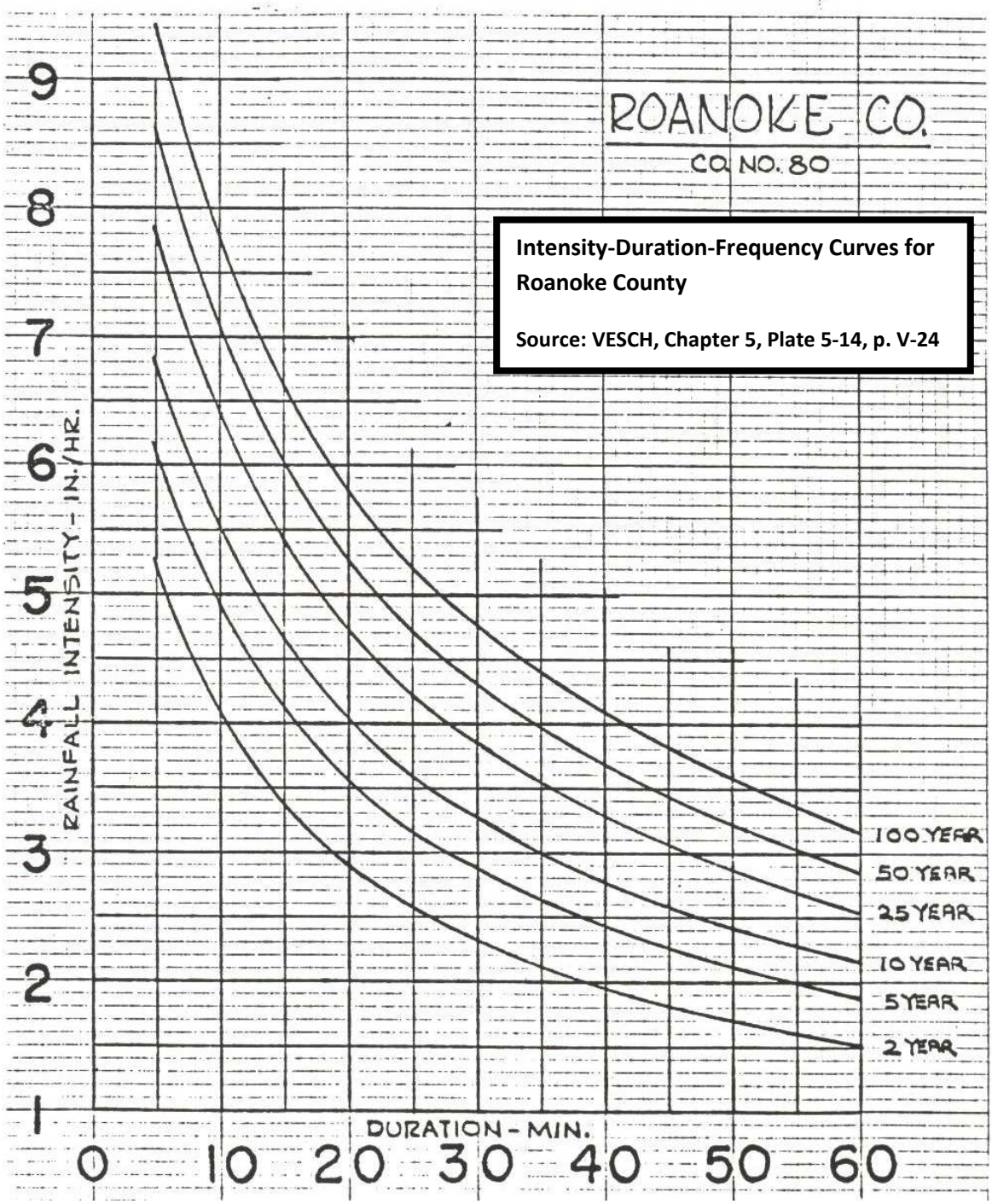

Source: 1999 VSMHB, Chapter 4, p. 4-18, Figure 4-8.

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 SCS method is recommended because it provides a means of estimating overland sheet flow time and shallow concentrated flow time as a function of readily available parameters such as land slope and land surface conditions. Regardless of which method is used, the result should be reasonable when compared to an average flow time over the total length of the watershed.

## Rainfall Intensity (I)

The rainfall intensity (I) is the average rainfall rate, in inches per hour, for a storm duration equal to the time of concentration for a selected return period (i.e., 1-year, 2-year, 10-year, 25-year, etc.). Once a particular return period has been selected, and the time of concentration has been determined for the drainage area, the rainfall intensity can be read from the appropriate rainfall Intensity-Duration-Frequency (I-D-F) curve for the geographic area in which the drainage area is located. Charts such as the two presented here for the City of Richmond and the County of Roanoke are included in the 1999 VSMHB (Appendix 4D) and the VESCH (Plates 5-4 to 5-18, p. V-14 to V-28), respectively, and were developed from data furnished by the National Weather Service for regions of Virginia.



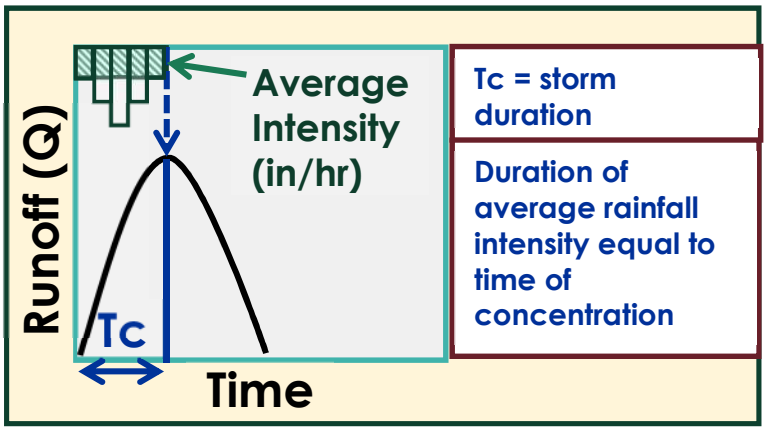



**Intensity-Duration-Frequency Curves for Roanoke County**

**Source: VESCH, Chapter 5, Plate 5-14, p. V-24**

## 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 = $T_c$ .

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

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

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

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

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

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

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

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

   Therefore, the accuracy of the rational method is dependent on the careful selection of a coefficient that is appropriate for the storm, soil, and land use conditions.

   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, it is recommended that the rational method only be used when the drainage area is less than or equal to 20 acres. The VSMP regulations allow for a maximum of 200 acres (9VAC25-870-72).

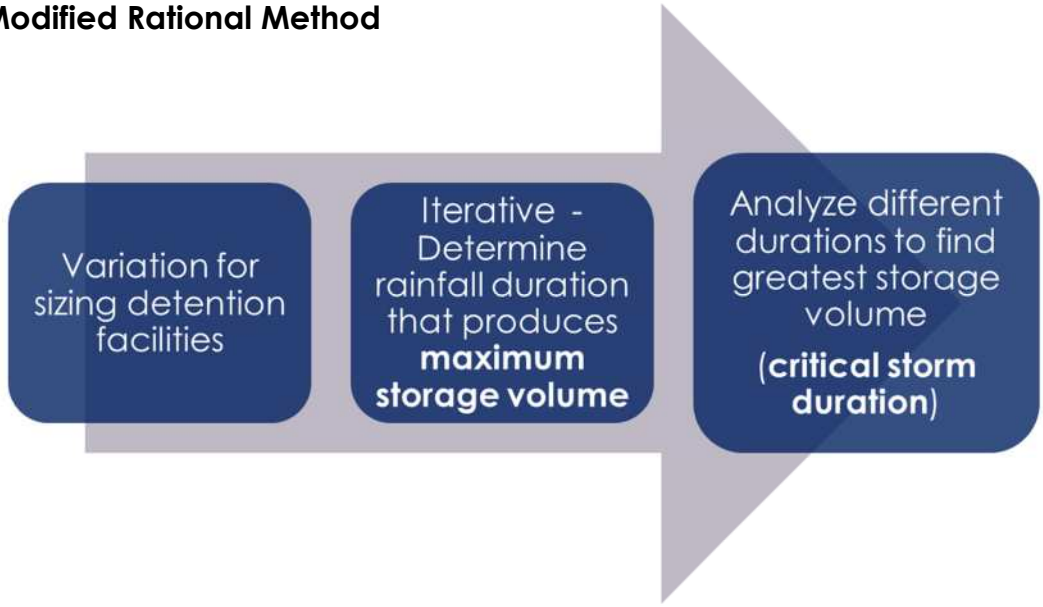
For larger watersheds, attenuation of peak flows through the drainage network begins to be a factor in determining peak discharge. While there are ways to adjust runoff coefficients (C factors) to account for the attenuation, or routing effects, it is better to use a hydrograph method or computer simulation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

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

**Key Points**

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

## 10c3. Modified Rational Method




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

### Modified Rational Method Assumptions

The Modified Rational Method is based on the following assumptions:

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

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

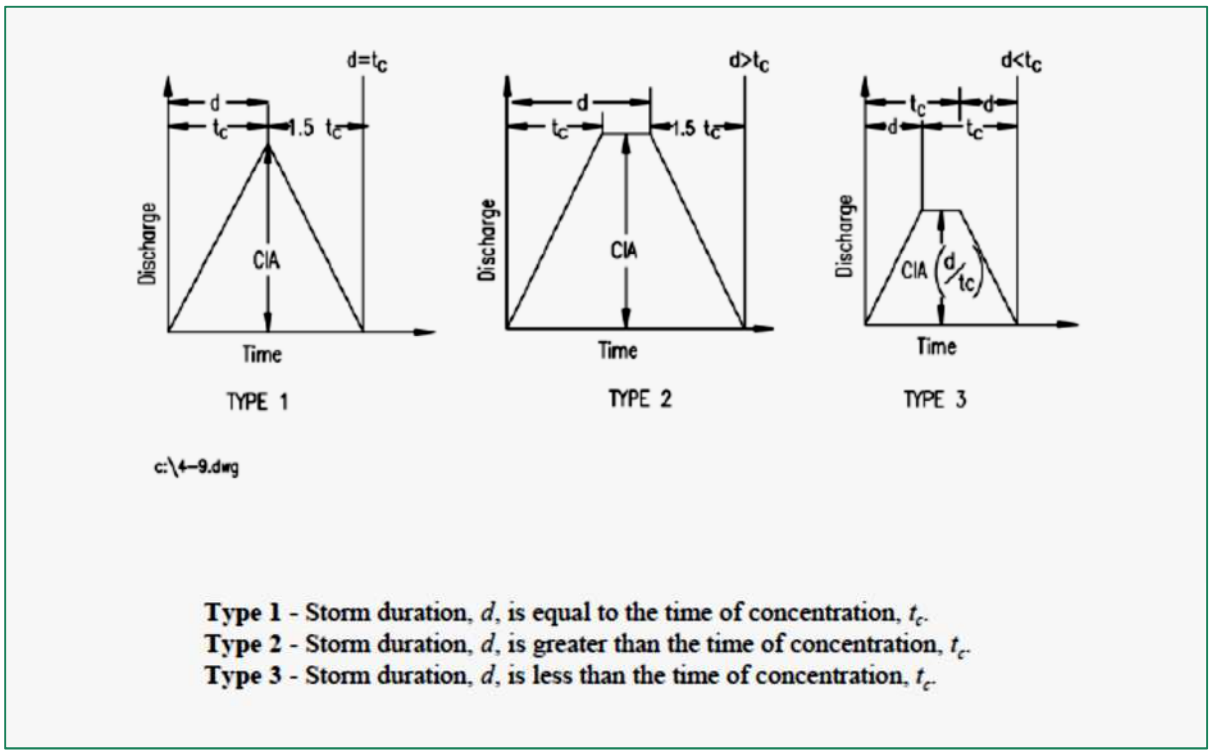
2. *The runoff hydrograph for a watershed can be approximated as triangular or trapezoidal in shape*.

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

## Modified Rational Method Limitations

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

**Modified Rational Method Runoff Hydrographs**
(Source: 1999 VSWMH; p. 4-26)




## Modified Rational Method Design Parameters

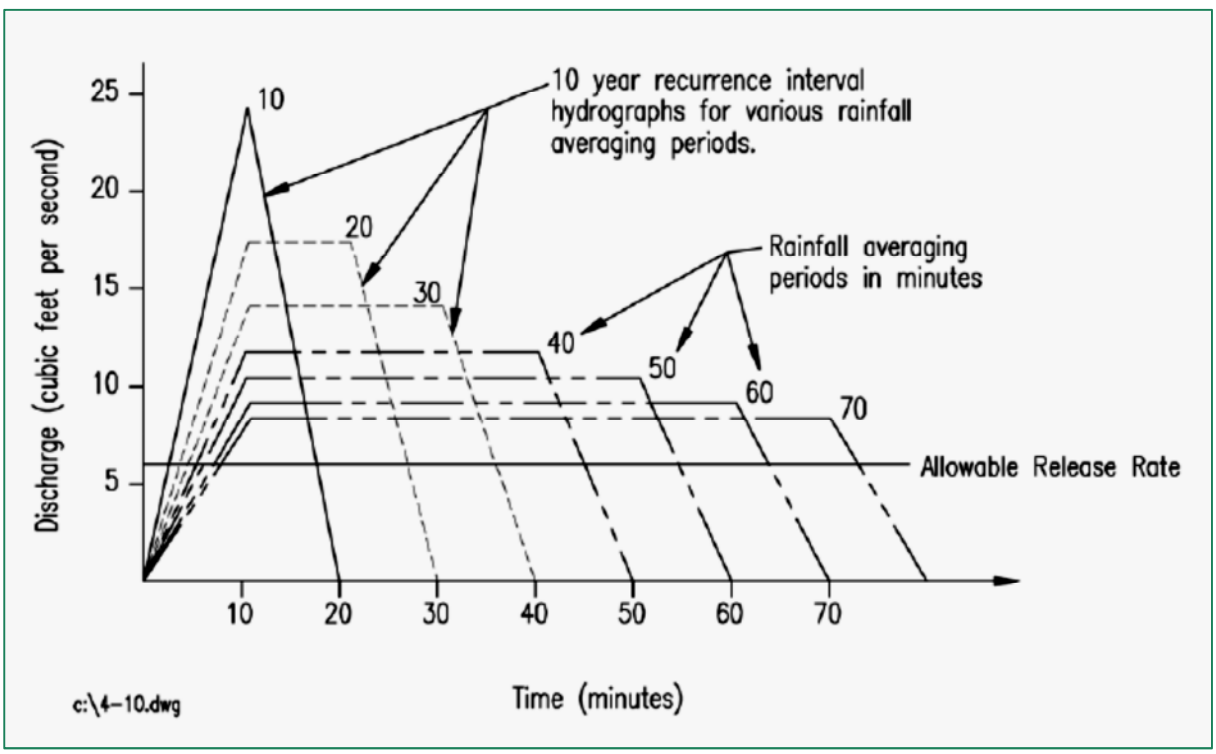
The equation Q = C x I x A (rational formula) is used to calculate the peak discharge for all three hydrographs shown above. Notice that the only difference between the rational method and the modified rational method is the incorporation of the storm duration (d) into the modified rational method to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

The rational method generates the peak discharge that occurs when the entire watershed is contributing to the peak (at a time t = $T_c$) and ignores the effects of a storm which lasts longer than time t. The modified rational method, however, considers storms with a longer duration than the watershed $T_c$ , which may have a smaller or larger peak rate of discharge, but will produce a greater volume of runoff (area under the hydrograph) associated with the longer

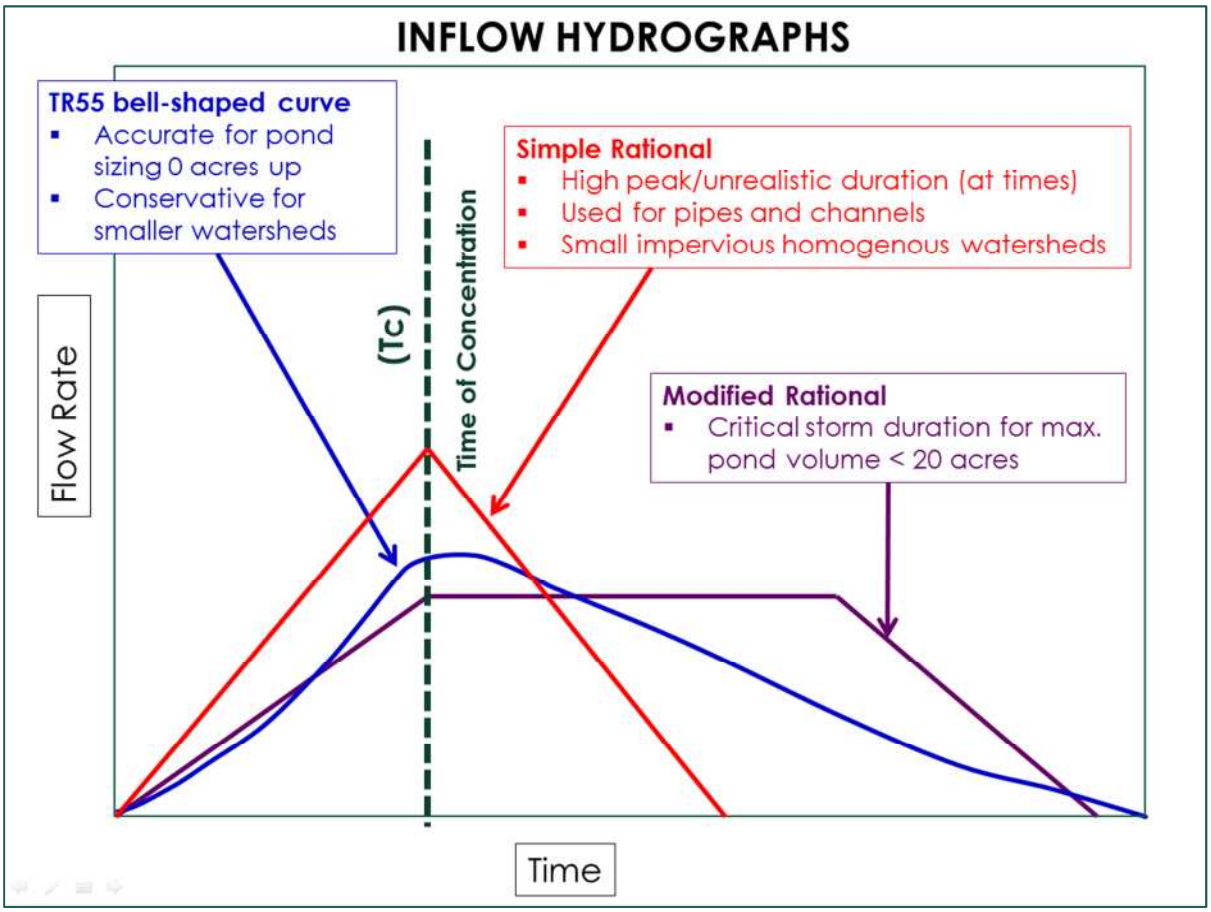
duration of rainfall. The figure below shows a family of hydrographs representing storms of different durations. The storm duration which generates the greatest volume of runoff may not necessarily produce the greatest peak rate of discharge.

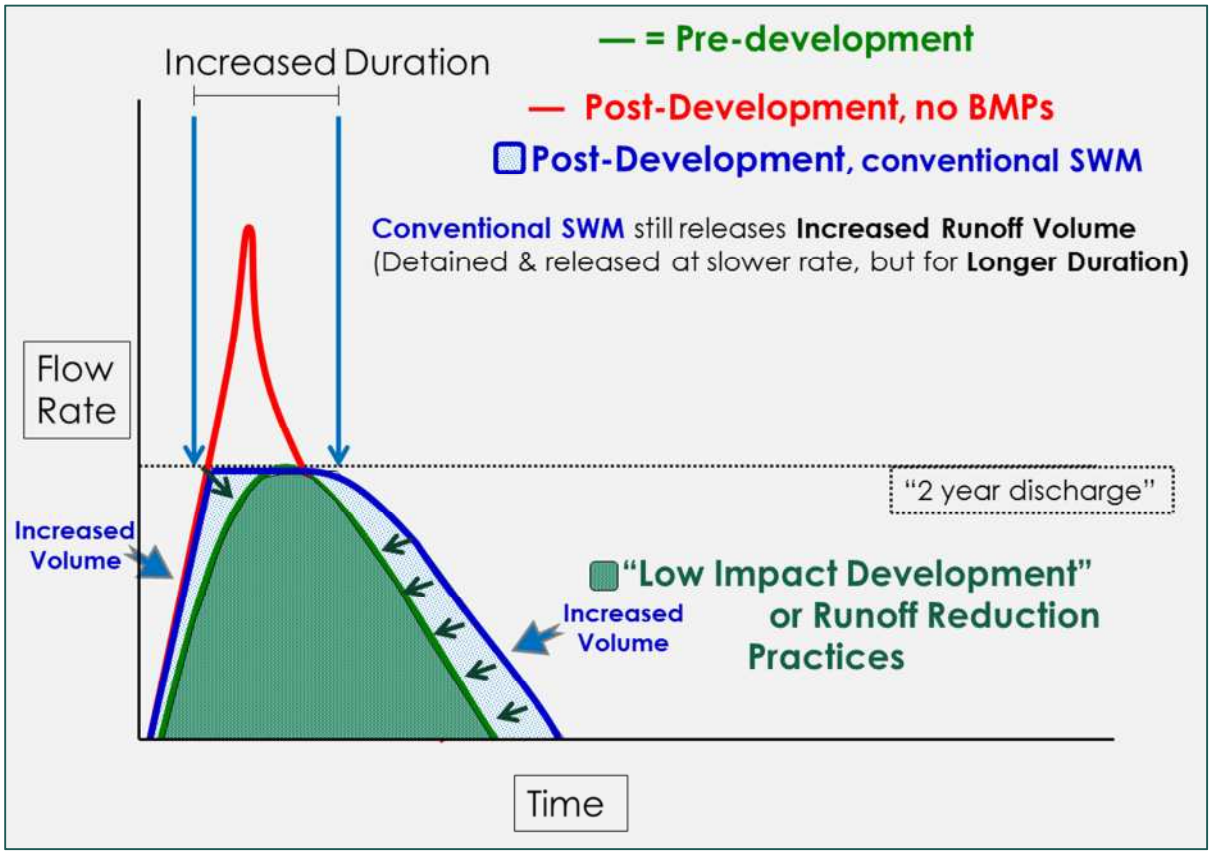
Note that the duration of the receding limb of the hydrograph is set to equal the time of concentration ($T_c$), or 1.5 times $T_c$. The direct solution, which is discussed in Chapter 5 of the 1999 VSWMH, uses 1.5 times $T_c$ as the receding limb. This is justified since it is more representative of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

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




*Modified Rational Method Runoff Hydrographs* (Source: 1999 VSWMH; p. 4-27)


INFLOW HYDROGRAPHS
TR55 bell-shaped curve
Accurate for pond sizing 0 acres up
Conservative for smaller watersheds
Simple Rational
High peak/unrealistic duration (at times)
Used for pipes and channels
Small impervious homogenous watersheds
Modified Rational
Critical storm duration for max. pond volume < 20 acres
Time of Concentration
(Tc)
Flow Rate
Time


Increased Duration
— = Pre-development
— Post-Development, no BMPs
Post-Development, conventional SWM
Conventional SWM still releases Increased Runoff Volume
(Detained & released at slower rate, but for Longer Duration)
Flow Rate
"2 year discharge"
Increased Volume
"Low Impact Development" or Runoff Reduction Practices
Increased Volume
Time

## Notes

## Module 10 Work Problems

# Rational Method

Most accurate when used on small, impervious and homogeneous watersheds (<200 acres)

$$Q = C * i * A$$

| | | |
|---|---|---|
| Q | = | peak discharge / rate of runoff (cu. Ft. / sec.) |
| C | = | runoff coefficient<br>(*Table 5-2, page V-29*) |
| i | = | average rainfall intensity (inches / hour)<br>(*Using Storm Duration – to determine the intensity (i) for the design Storm frequency (2yr, 10yr, etc.) from the I-D-F curves on pages V-14 to V-28*) |
| A | = | Drainage area (acres) |

# NRCS – TR-55 Method

Technical Release – 55, Urban Hydrology for Small Watersheds

$$q_p = q_u * A_m * Q * F_p$$

| | | |
|---|---|---|
| $q_p$ | = | peak discharge (cfs) |
| $q_u$ | = | Unit peak runoff (csm/in)<br>(*Plate 5-25, page V-55*) |
| $A_m$ | = | drainage area (sq. miles) |
| Q | = | estimated runoff (inches)<br>(*Plate 5.22, page V-52*) |
| $F_p$ | = | pond and swamp adjustment factor<br>(*Table 5-10, page V-65*) |

| | | |
|---|---|---|
| CN | = | Curve Number (*Table 5-5, pages V-56 to V-59* |
| P | = | Rainfall (Plates 5-19 to 21, *pages V-49 to V-51*) |
| $I_a$ | = | Initial Abstraction (*Table 5-9, page V-64*) |

Follow the step-by-step procedure and worksheets starting on page V-31 to solve the peak discharge method. (*Use Plates and Tables provided on pages V-49 to V-65.*)

**Note:** 1 square mile = 640 acres

**Time of Concentration** ESCH V-4

Overland Flow <300 feet

1. **What is the Time of Concentration, T(minutes), for a Length, L(feet) = 200 feet, over an average grass surface, with a 4% slope.**

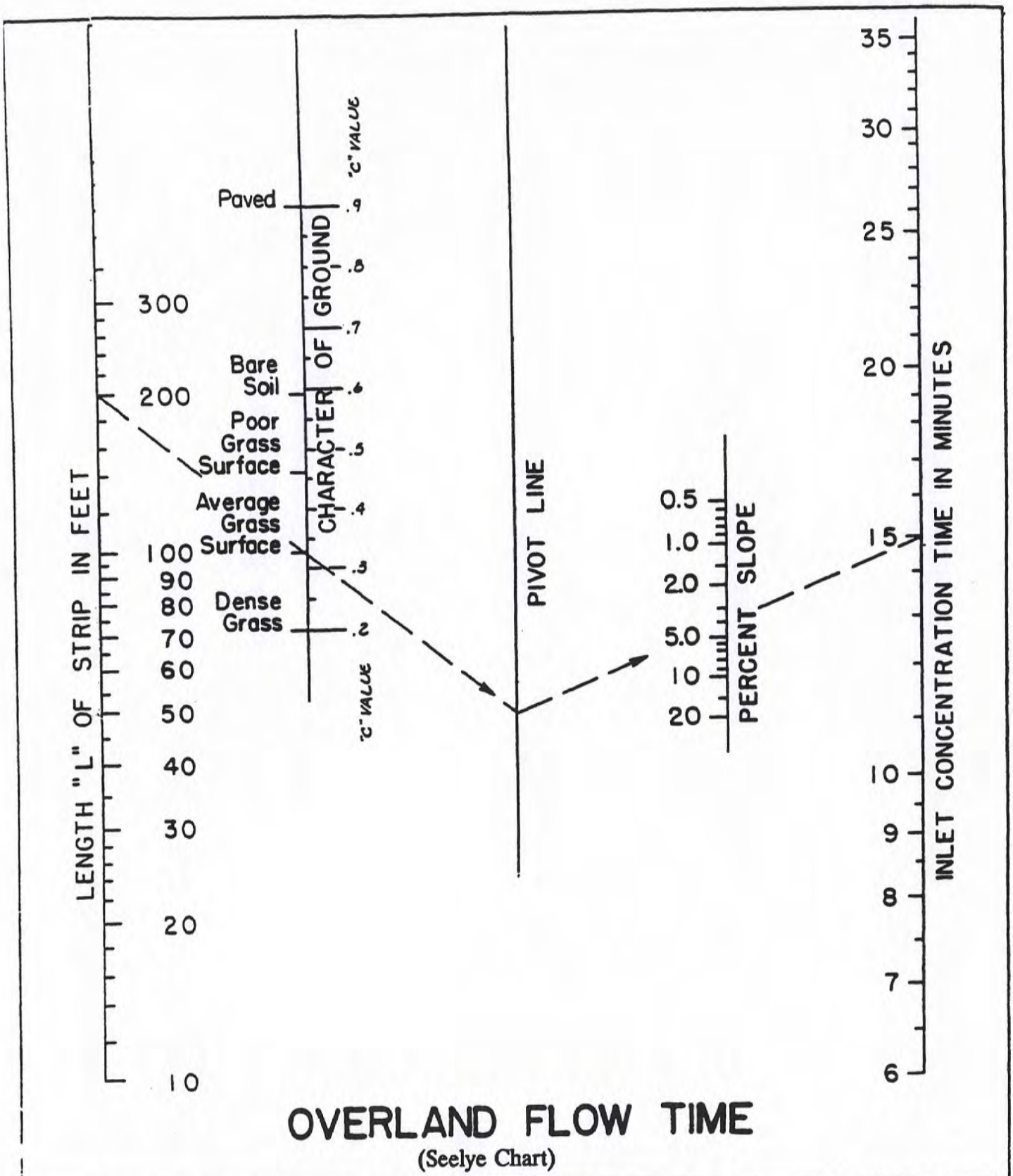
From ESCH V-11, Plate 5-1, Seelye Chart

Select on left vertical axis the Length = (  )feet

From that point draw a line through Average Grass Surface to pivot line.

Draw a line from pivot line through the Slope = (  )%

Read on right vertical axis, Time of Concentration, T = (  )minutes.




OVERLAND FLOW TIME
(Seelye Chart)

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

Plate 5-1

Shallow Concentrated Flow < 1000 feet

2. **For shallow concentrated flow over pavement for 500 feet (L) and 2% slope (s), what is the Time of Concentration?**

From ESCH V-11, Plate 5-2

Convert slope in % to slope in feet/foot:

$$S = \frac{s}{100}$$

*Where:*
*s= Slope (%)*
*S = Slope (feet/foot)*

Slope, S = (  )% / 100 = (  )feet/foot

On the left vertical axis select the Slope, S = (  )feet/foot

Read over horizontally to line marked "Paved", and read down to determine

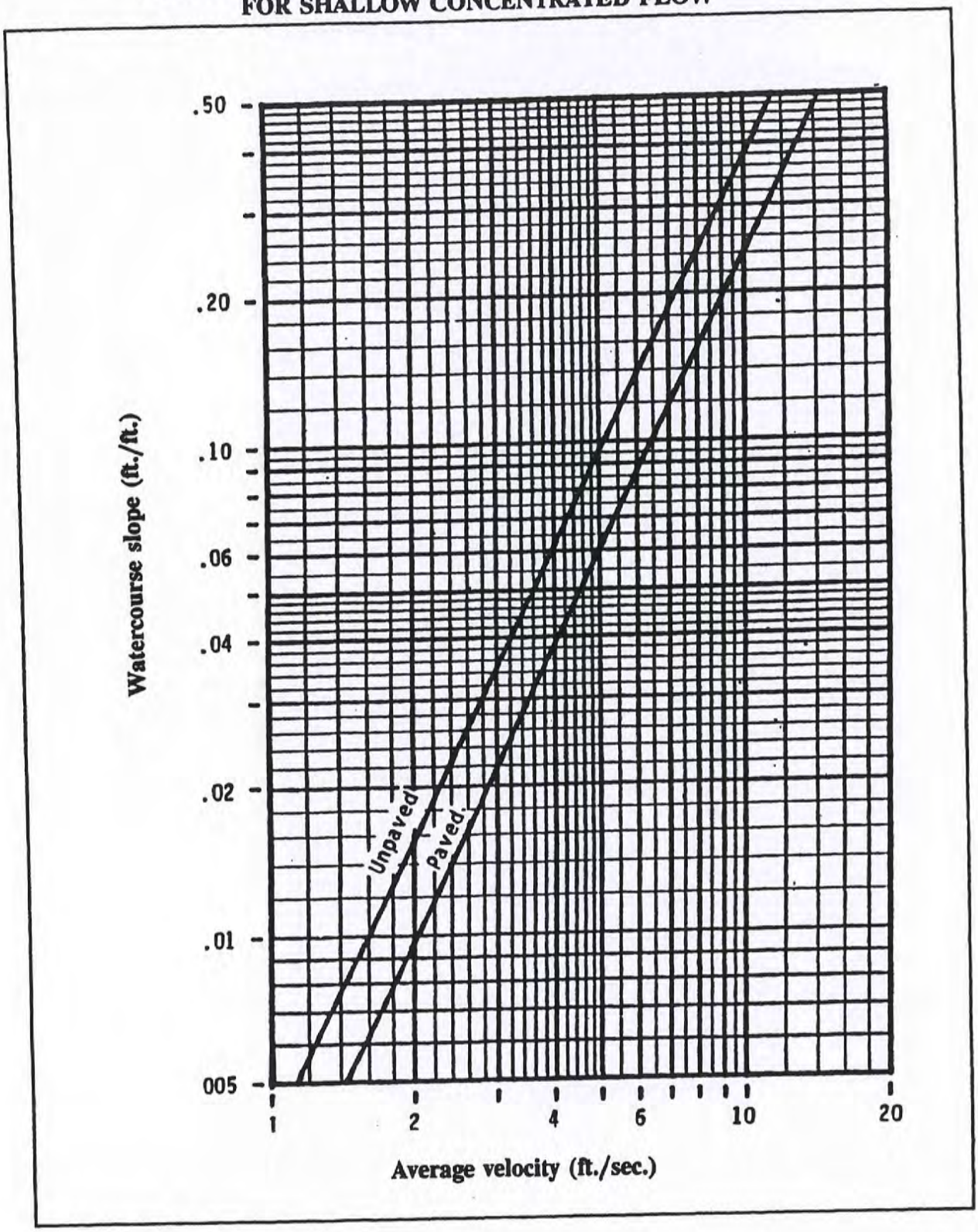
Average Velocity, V = (  )feet/second

$$T = \frac{L}{60 \times V}$$

T (Time of Concentration, minutes) = L (Length, feet) / [60 x V (Velocity (feet/second)]

T = (  )feet / [60 x (  )feet/second] = (  )minutes

## AVERAGE VELOCITIES FOR ESTIMATING TRAVEL TIME FOR SHALLOW CONCENTRATED FLOW




Source: USDA-SCS

Plate 5-2

Channel Flow

3. **Given a channel with a hydraulic radius of 2.0, a slope equaling 0.5%, and a Manning's Roughness Coefficient, n = .02, what is the Time of Concentration of flow through a channel over a length of 1000 feet?**

From the Nomograph for Solution of Manning's Equations – Attached

On left vertical axis select Hydraulic Radius = (  )

Draw line through Slope = (  )feet/foot to pivot line

From pivot line draw line through Manning's Roughness Coefficient, n = (  )

Read from right vertical axis the Velocity, V = (  )feet/second

$$T = \frac{L}{60 \times V}$$

T (Time of Concentration, minutes) = L (Length, feet) / [60 x V (Velocity (feet/second)]

T = (  )feet / [60 x (  )feet/second] = (  )minutes

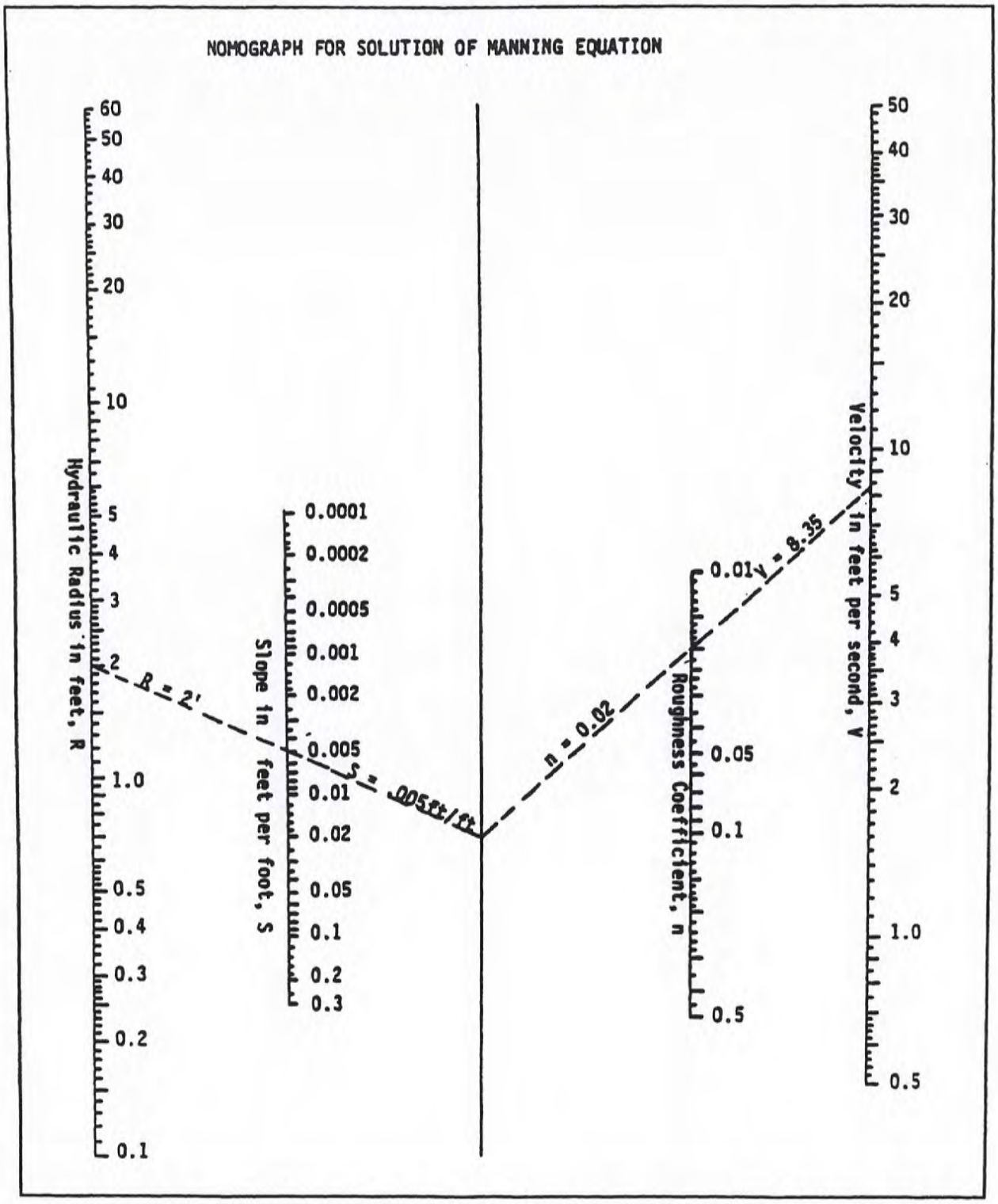
4. **What is the total time of concentration?**

Total Time of Concentration,

T = Overland Flow Time + Shallow Concentrated Flow Time + Channel Flow Time

T = (  )minutes + (  )minutes + (  )minutes = (  )minutes

# NOMOGRAPH FOR SOLUTION OF MANNING EQUATION




Source: VDOT

Plate 5-24

**Rational Formula** ESCH V-3

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

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

C, Runoff Coefficient, is found from (ESCH V-29, Table 5-2)

T(minutes), Time of Concentration, is calculated for:
overland flow (ESCH V-11, Plate 5-1)
shallow concentrated (ESCH V-12, Plate 5-2)
channel flow (ESCH V-13, Plate 5-3)

i, (inches/hour), Average Rainfall Intensity, from (ESCH V-14 to V-280

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

1. **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 woodlands, and with the remainder in lawn on heavy soils with slopes greater than 7%, what is the weighted average runoff coefficient based upon the highest values of individual runoff coefficients?**

Convert roof top area from square feet to acres (1 acre = 43,560 square feet):

A (Area of roof top, acre) = square feet of roof top / 43,560 (square feet)

A (acres) = ( ) square feet / 43,560 square feet = ( ) acres

From ESCH V-29, Table 5-2:

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

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

**2. 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?**

From ESCH V-14:

Locate Time of Concentration, T(minutes) = (  )minutes on horizontal axis.

Locate curve for given storm frequency = (  )year.

From horizontal axis, read up to curve for given storm frequency, and read to left to vertical axis for rainfall intensity:

Rainfall intensity, i (in/hr) = (  )in/hr.

Weighted average runoff coefficient, calculated from previous problem, C = (  ).

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

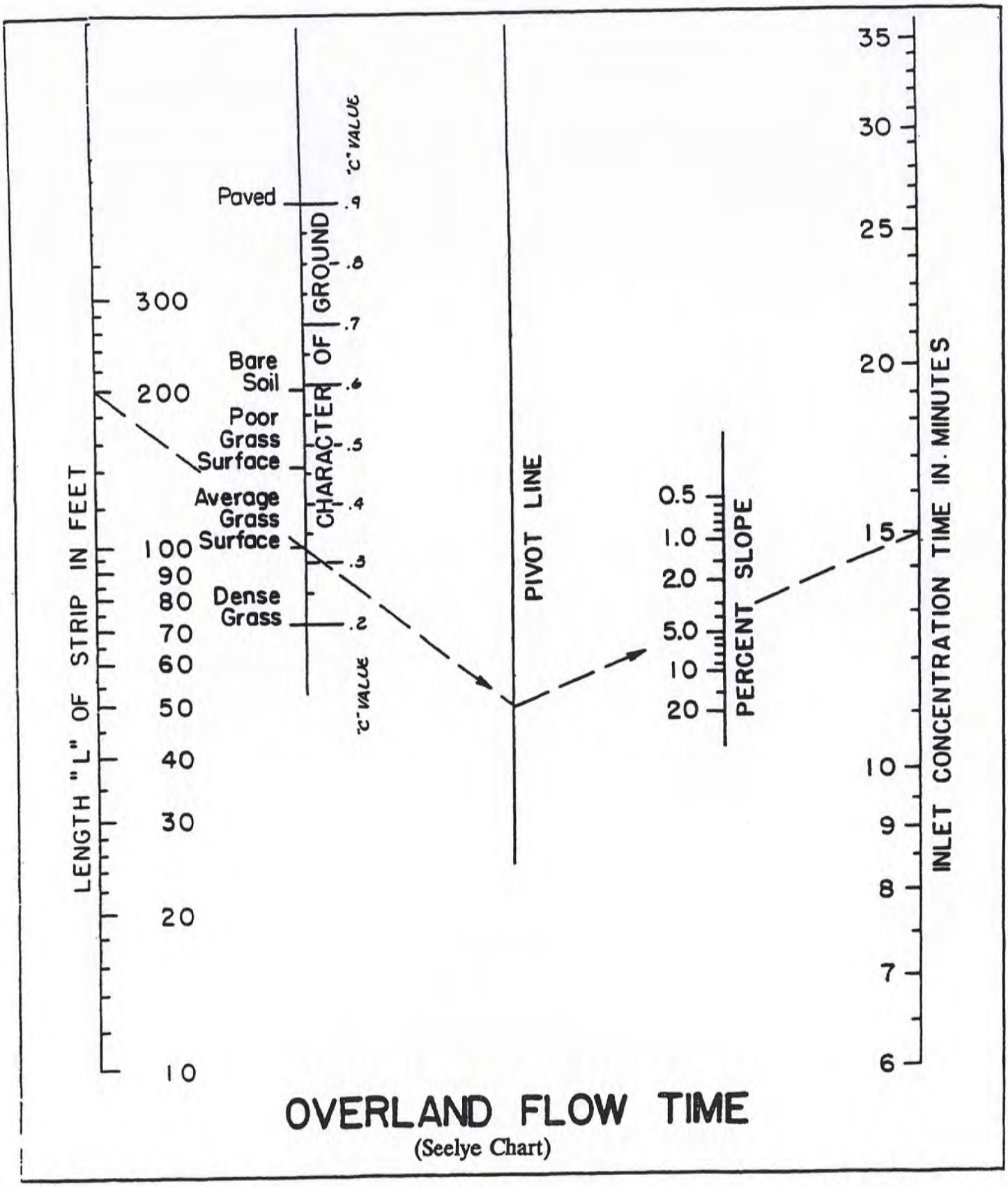
Q (Peak rate of runoff, cfs) = (  ) x (  ) x (  ) = (  )cfs

# TABLE 5-2
# VALUES OF RUNOFF COEFFICIENT (C) FOR RATIONAL FORMULA

| Land Use | C | Land Use | C |
|---|---|---|---|
| Business: | | Lawns: | |
| Downtown areas | 0.70-0.95 | Sandy soil, flat, 2% | 0.05-0.10 |
| Neighborhood areas | 0.50-0.70 | Sandy soil, average, 2-7% | 0.10-0.15 |
| | | Sandy soil, steep, 7% | 0.15-0.20 |
| | | Heavy soil, flat, 2% | 0.13-0.17 |
| | | Heavy soil, average, 2-7% | 0.18-0.22 |
| | | Heavy soil, steep, 7% | 0.25-0.35 |
| Residential: | | Agricultural land: | |
| Single-family areas | 0.30-0.50 | Bare packed soil | |
| Multi units, detached | 0.40-0.60 | * Smooth | 0.30-0.60 |
| Multi units, attached | 0.60-0.75 | * Rough | 0.20-0.50 |
| Suburban | 0.25-0.40 | Cultivated rows | |
| | | * Heavy soil, no crop | 0.30-0.60 |
| | | * Heavy soil, with crop | 0.20-0.50 |
| | | * Sandy soil, no crop | 0.20-0.40 |
| | | * Sandy soil, with crop | 0.10-0.25 |
| | | Pasture | |
| | | * Heavy soil | 0.15-0.45 |
| | | * Sandy soil | 0.05-0.25 |
| | | Woodlands | 0.05-0.25 |
| Industrial: | | Streets: | |
| Light areas | 0.50-0.80 | Asphaltic | 0.70-0.95 |
| Heavy areas | 0.60-0.90 | Concrete | 0.80-0.95 |
| | | Brick | 0.70-0.85 |
| Parks, cemeteries | 0.10-0.25 | Unimproved areas | 0.10-0.30 |
| Playgrounds | 0.20-0.35 | Drives and walks | 0.75-0.85 |
| Railroad yard areas | 0.20-0.40 | Roofs | 0.75-0.95 |

Note: The designer must use judgement to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lowest C values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the highest C values.

Source: American Society of Civil Engineers



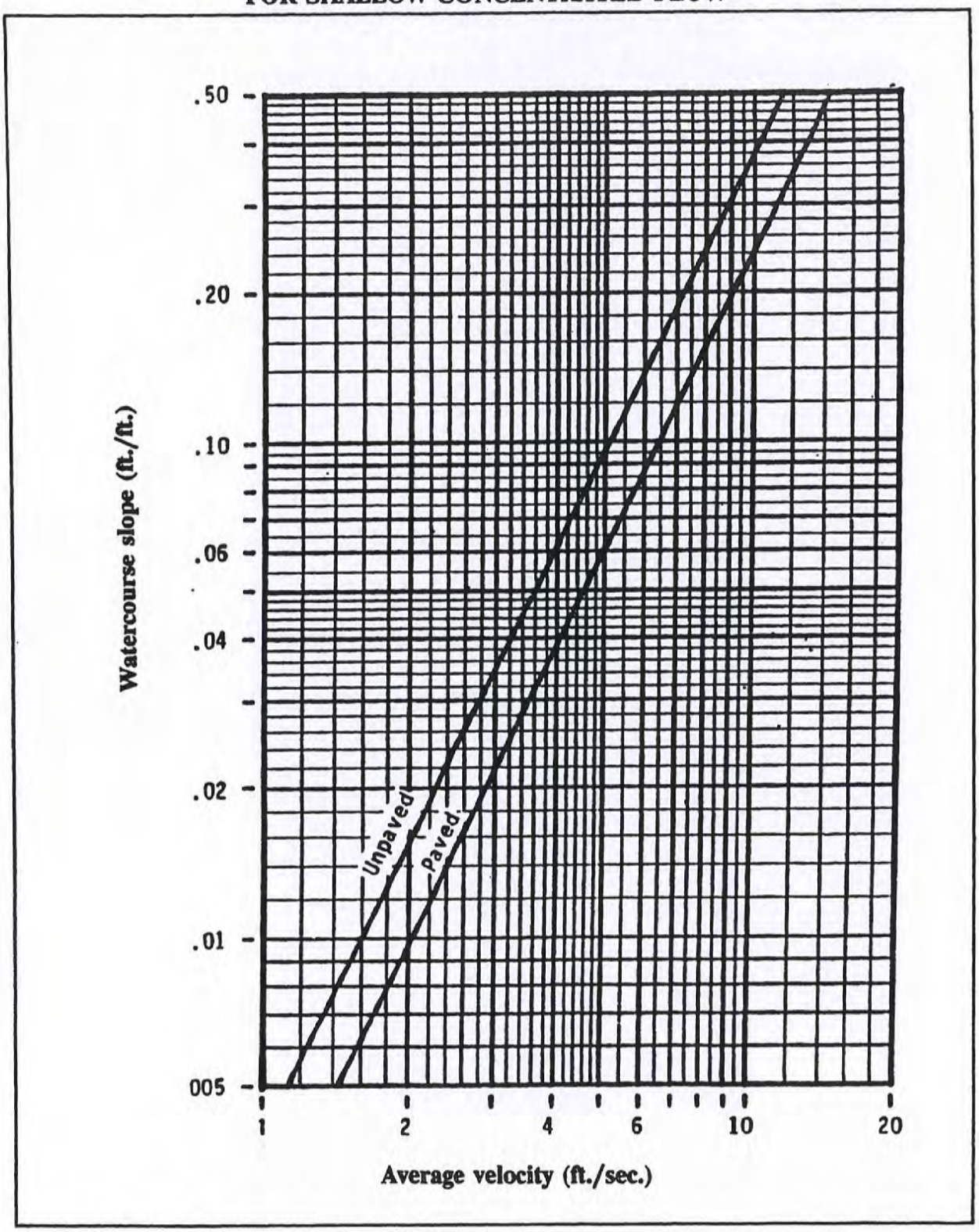

# OVERLAND FLOW TIME

(Seelye Chart)

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

Plate 5-1

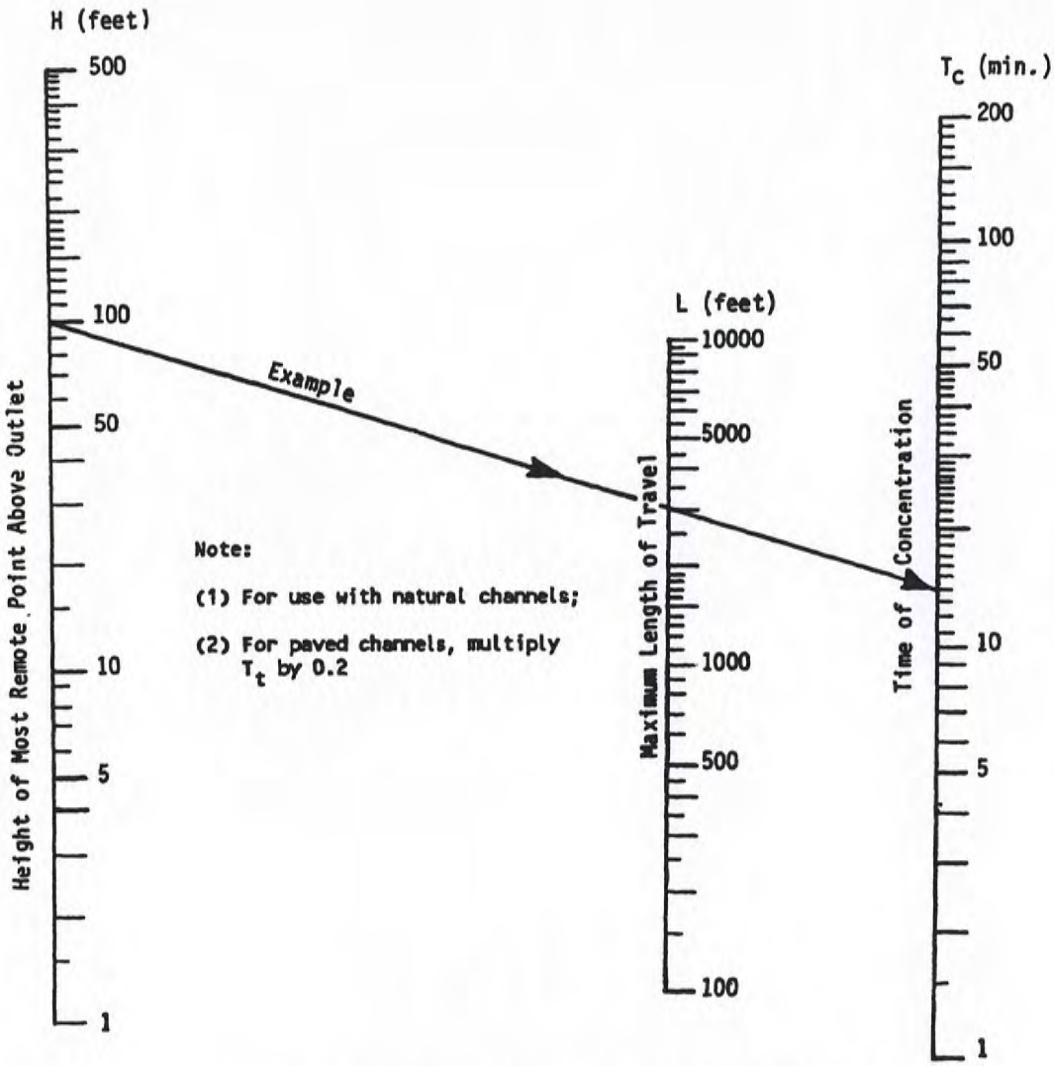
## AVERAGE VELOCITIES FOR ESTIMATING TRAVEL TIME FOR SHALLOW CONCENTRATED FLOW




Source: USDA-SCS

Plate 5-2

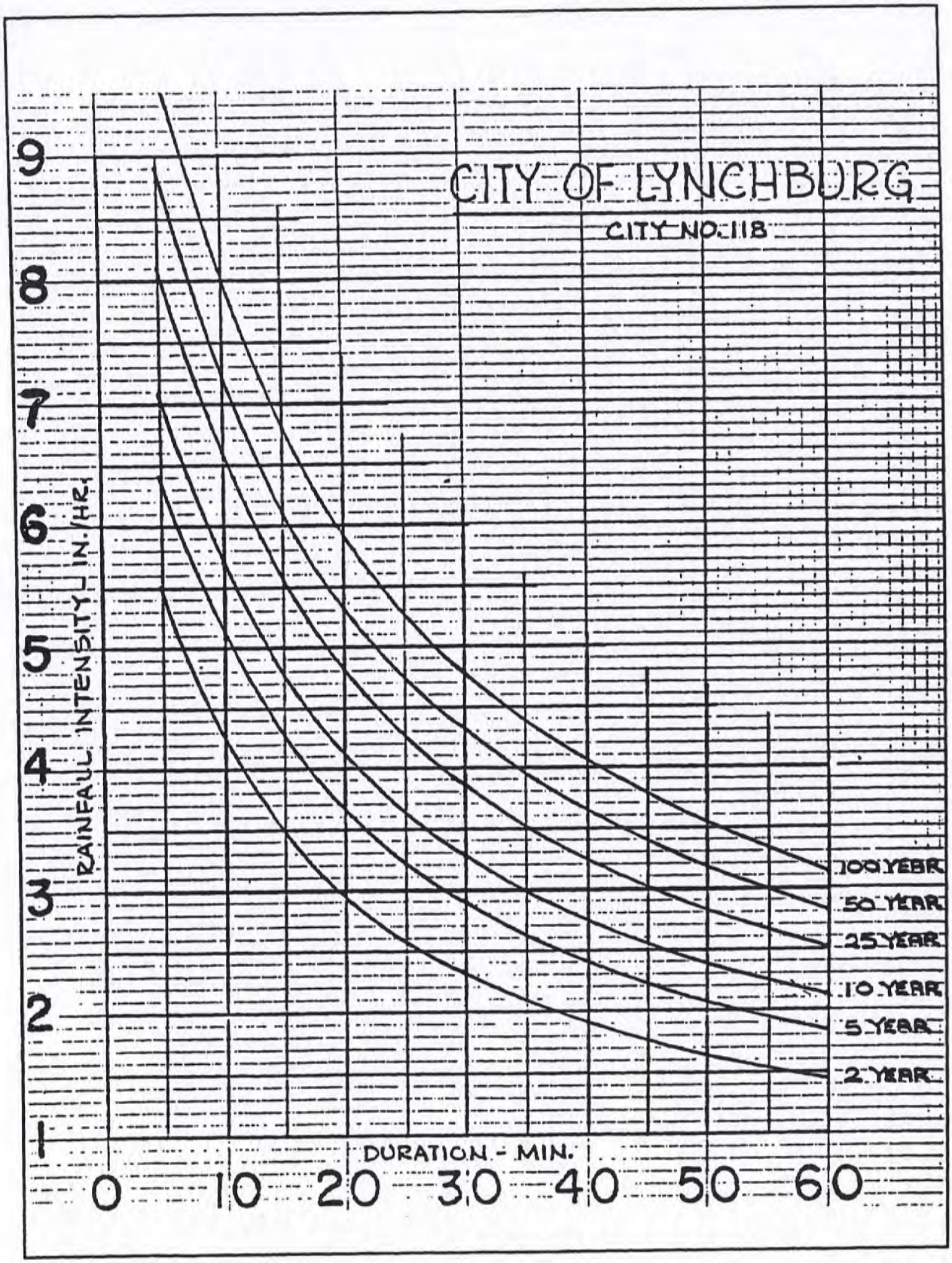
## TRAVEL TIME FOR CHANNEL FLOW
## (Kirpich Chart)




TIME OF CONCENTRATION OF SMALL DRAINAGE BASINS

Source: VDOT

Plate 5-3




Source: VDOT

Plate 5-4