DEQ Certification Class Presentations

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July 2024

Virginia Department of Environmental Quality

Module 9

Hydrology for Plan Reviewers

VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Module 9 Contents

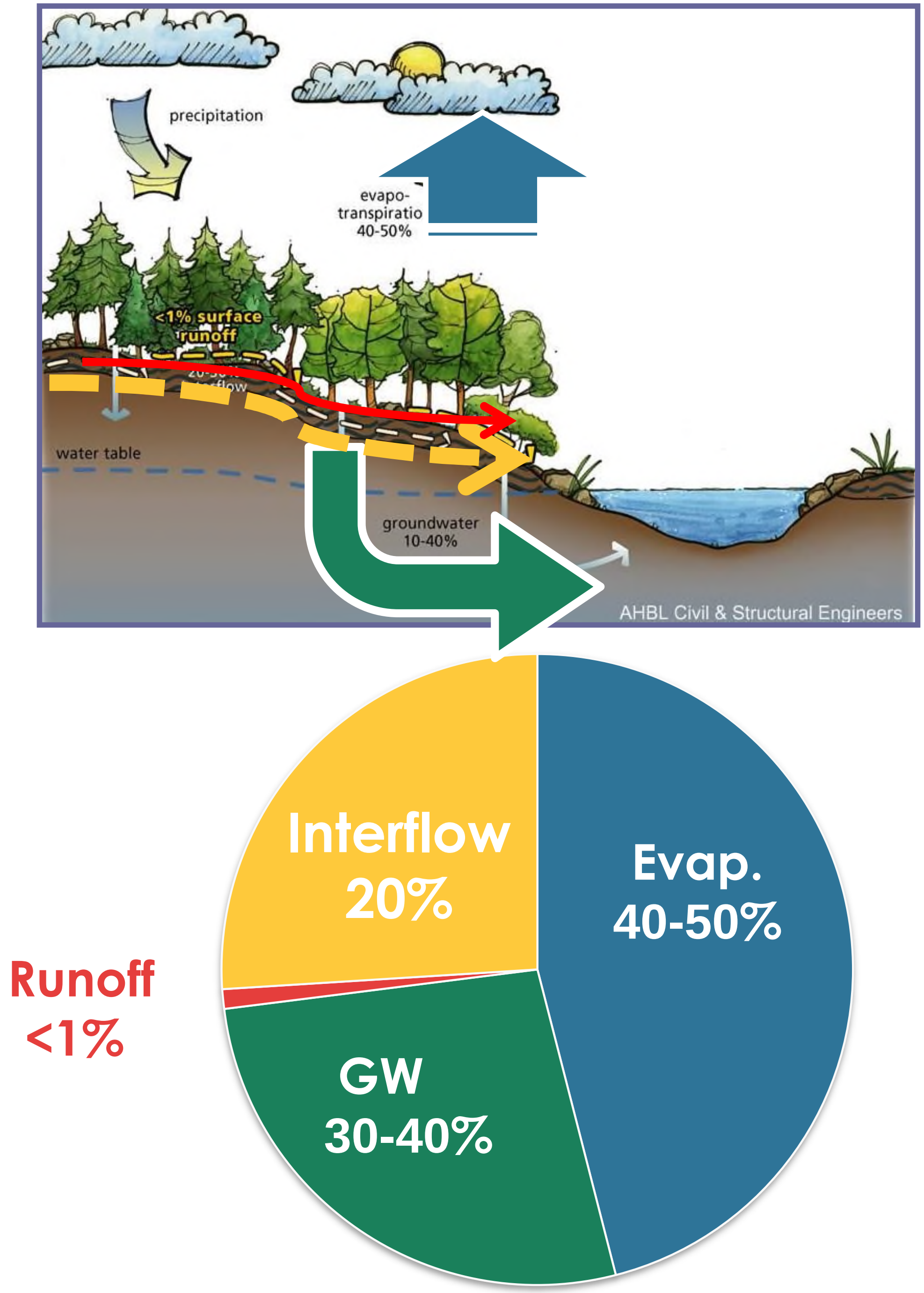
VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Module 9a.

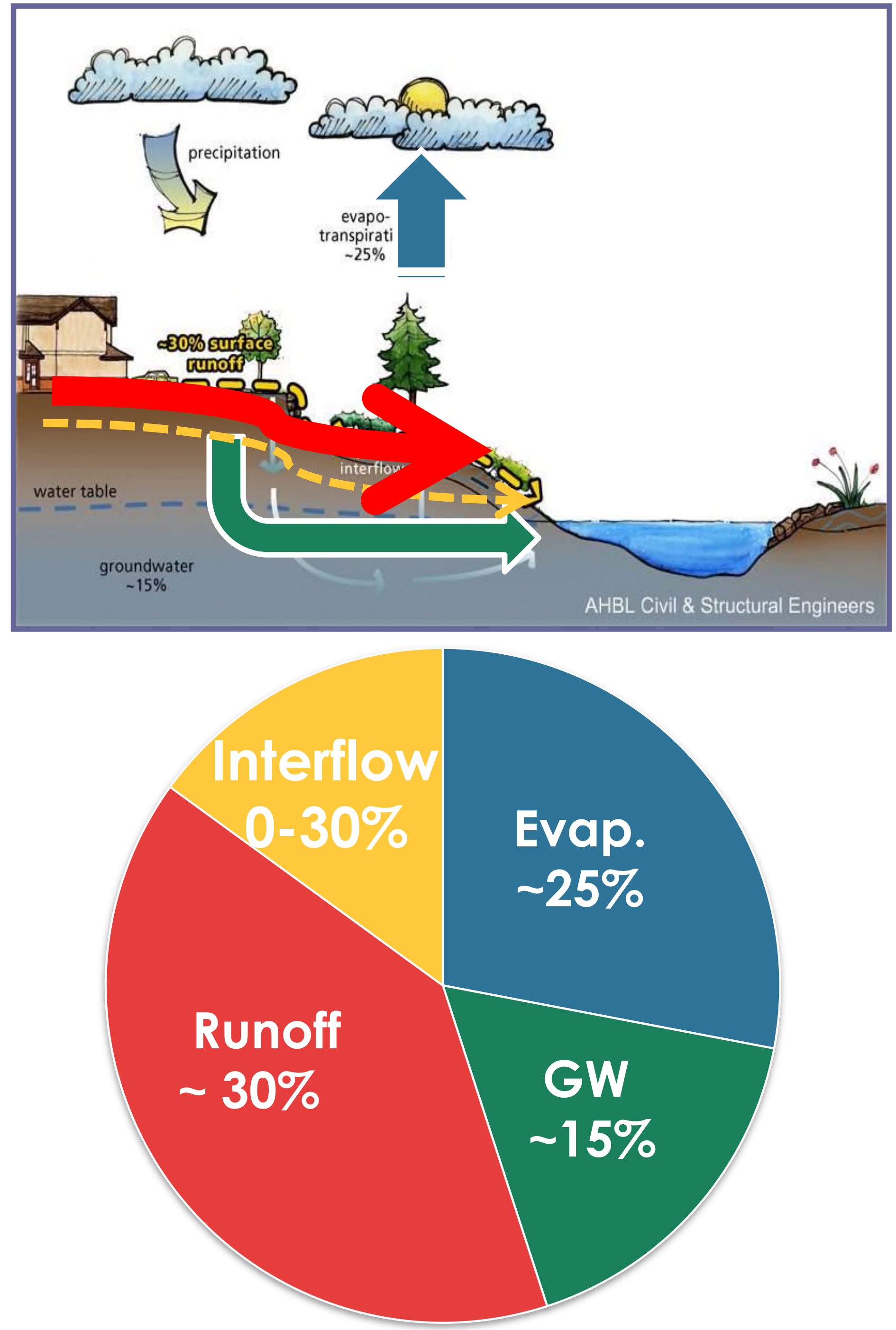
Hydrologic Cycle

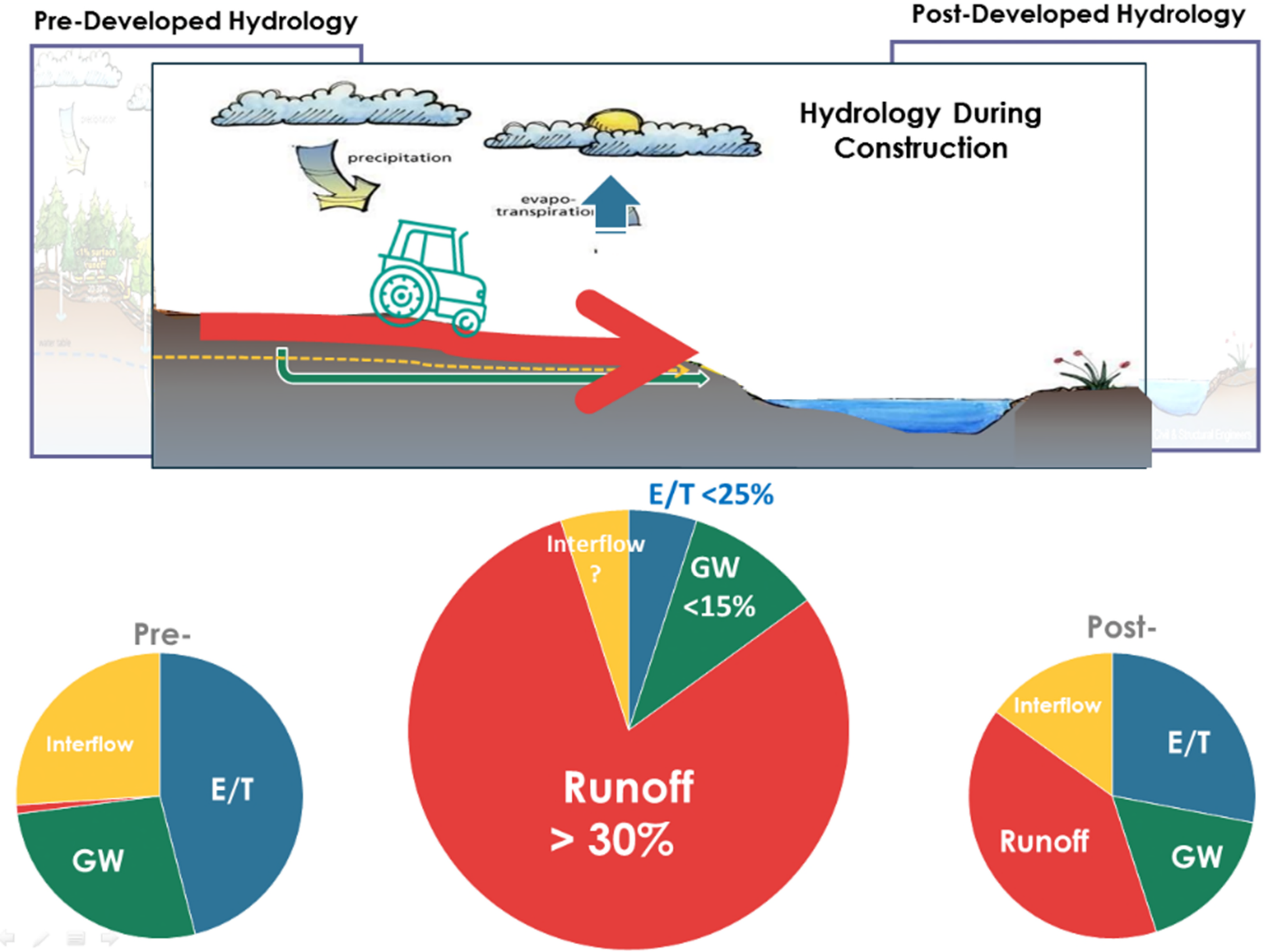
VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Pre-Developed Hydrology



Post-Developed Hydrology





Pre-Developed Hydrology
Post-Developed Hydrology
Hydrology During Construction
precipitation
evapo-transpiration
E/T <25%
Interflow ?
GW <15%
Runoff > 30%
Pre-
Interflow
E/T
GW
Post-
Interflow
E/T
Runoff
GW

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Module 9b.

Hydrology and Stormwater Engineering Concepts

Plan Reviewer for Erosion & Sediment Control

Water Quantity	Mimic Natural Processes

MS 19: Channel/Flood Protection (9VAC-25-875-600)

Discharge

Volume

Duration

- Adequate Channel
- Energy Balance Equation
- Localized Flooding
- Analyze to Limits of Analysis

Mimic Natural Processes

- Land Cover Types/Soils
- Minimize Impacts
- Environmental Site Design
- Using Runoff Reduction Method

Stormwater Engineering Concepts

- Plan reviewers must evaluate and review critical components of stormwater management
  - Understand basic engineering-related hydrology and hydraulics
  - Planning and design elements of stormwater management

Stormwater Engineering Concepts

- Hydrology
  - Drainage area characteristics and precipitation
  - Quantify volumes and flow rates
- Hydraulics:
  - Planning and design of SWM facilities, structures

Stormwater Engineering Concepts

- Hydrologic cycle complex
- Simulations inexact science
- Variables and dynamic relationships reduced to basic assumptions

Stormwater Engineering Concepts

- VESM Regs introduce additional tools (RR practices, ESD)
- More realistic channel protection for natural channels given current understanding

Stormwater Engineering Concepts

- Computational procedures used to comply with and evaluate water quantity technical criteria
  - Assumptions and critical errors

Stormwater Engineering Concepts

- VSWHB
- TR-55 (1986) and WinTR-55 (2006)
- National Engineering Handbook

Module 9c.

Understanding the Water Quantity Requirements

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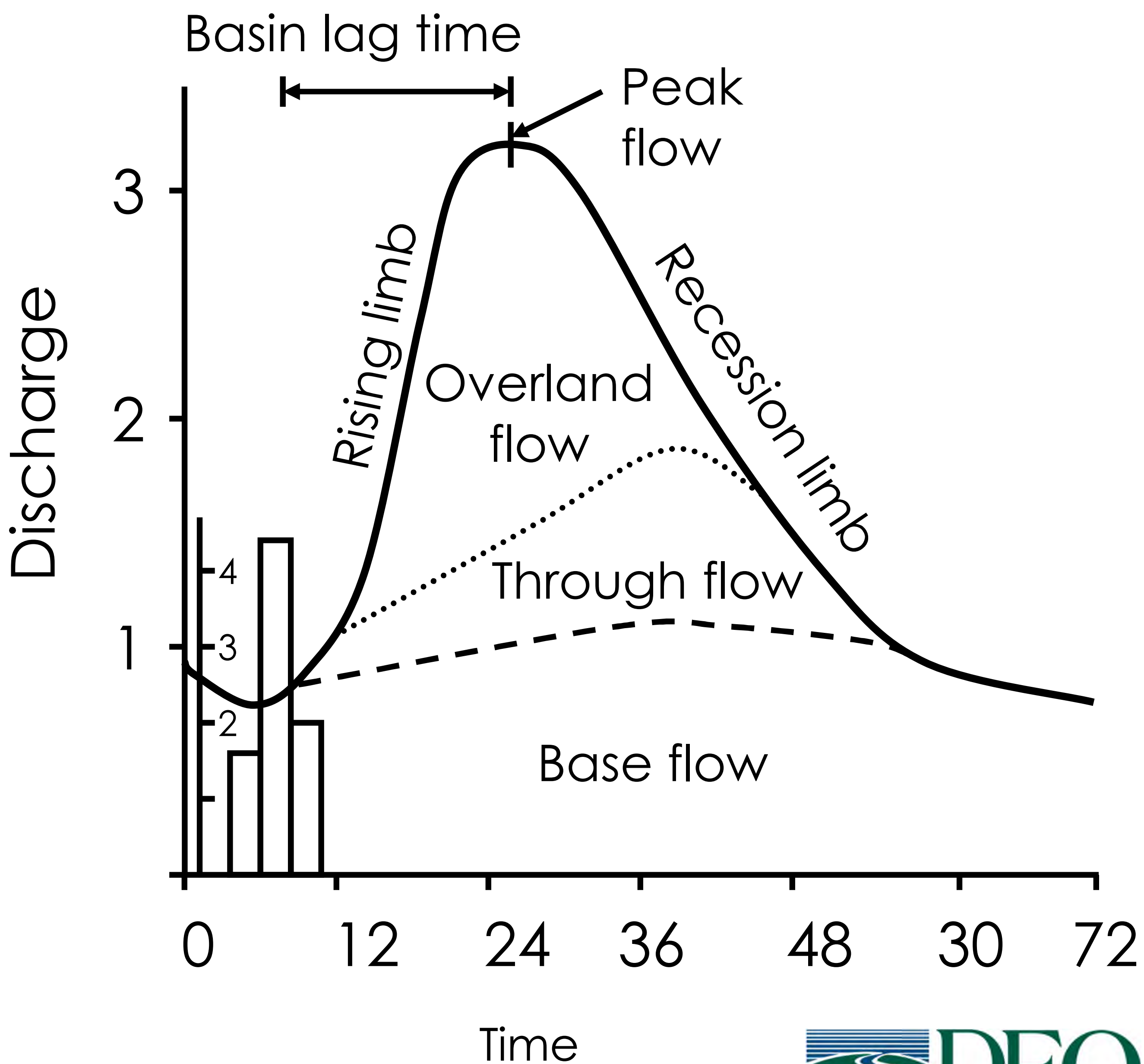
Rainfall-Runoff Relationships

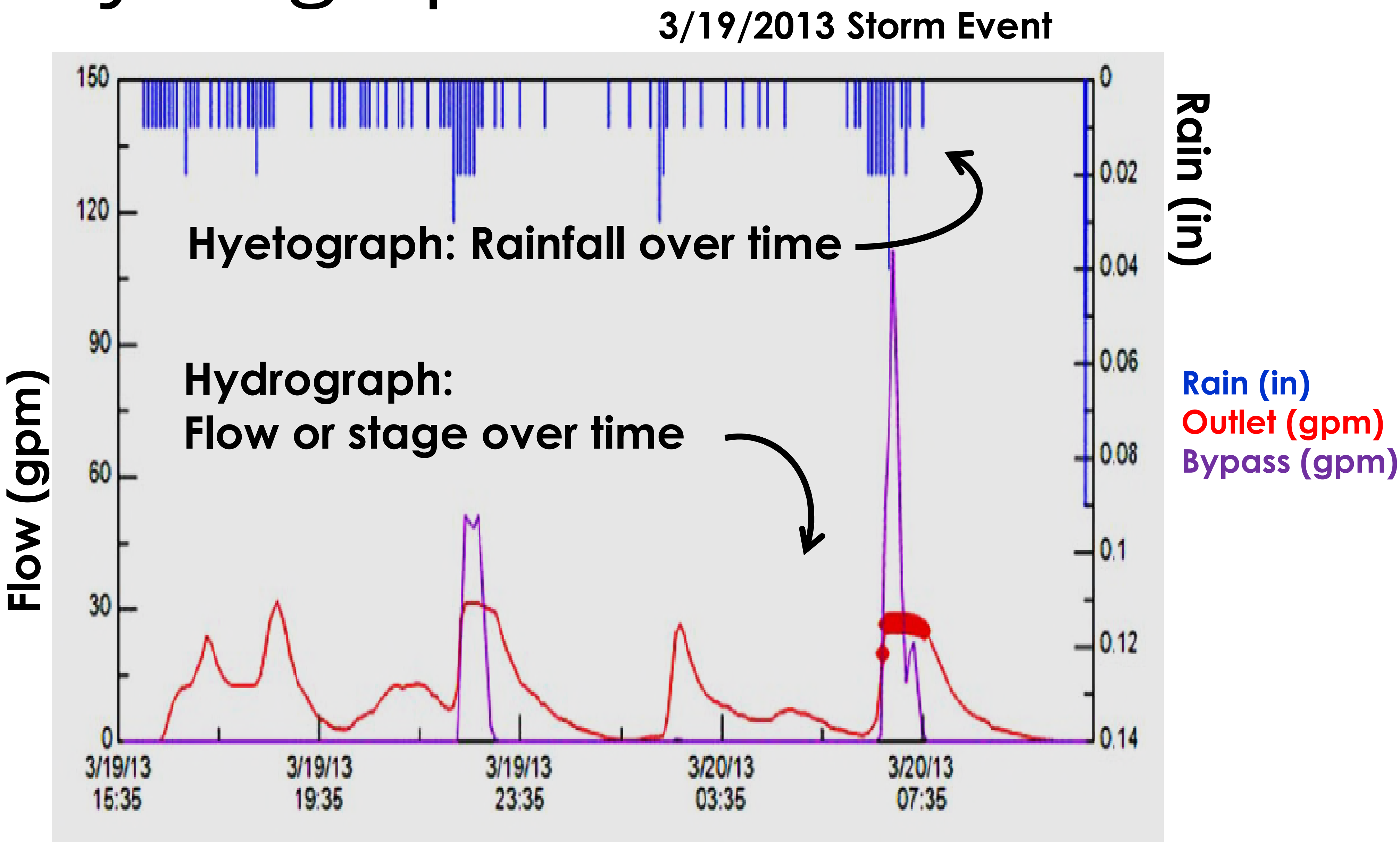
- Runoff generation
  - Rainfall loss (infiltration, depression storage)
  - Runoff movement across and through drainage area (topography, land cover, land use)

Hydrographs

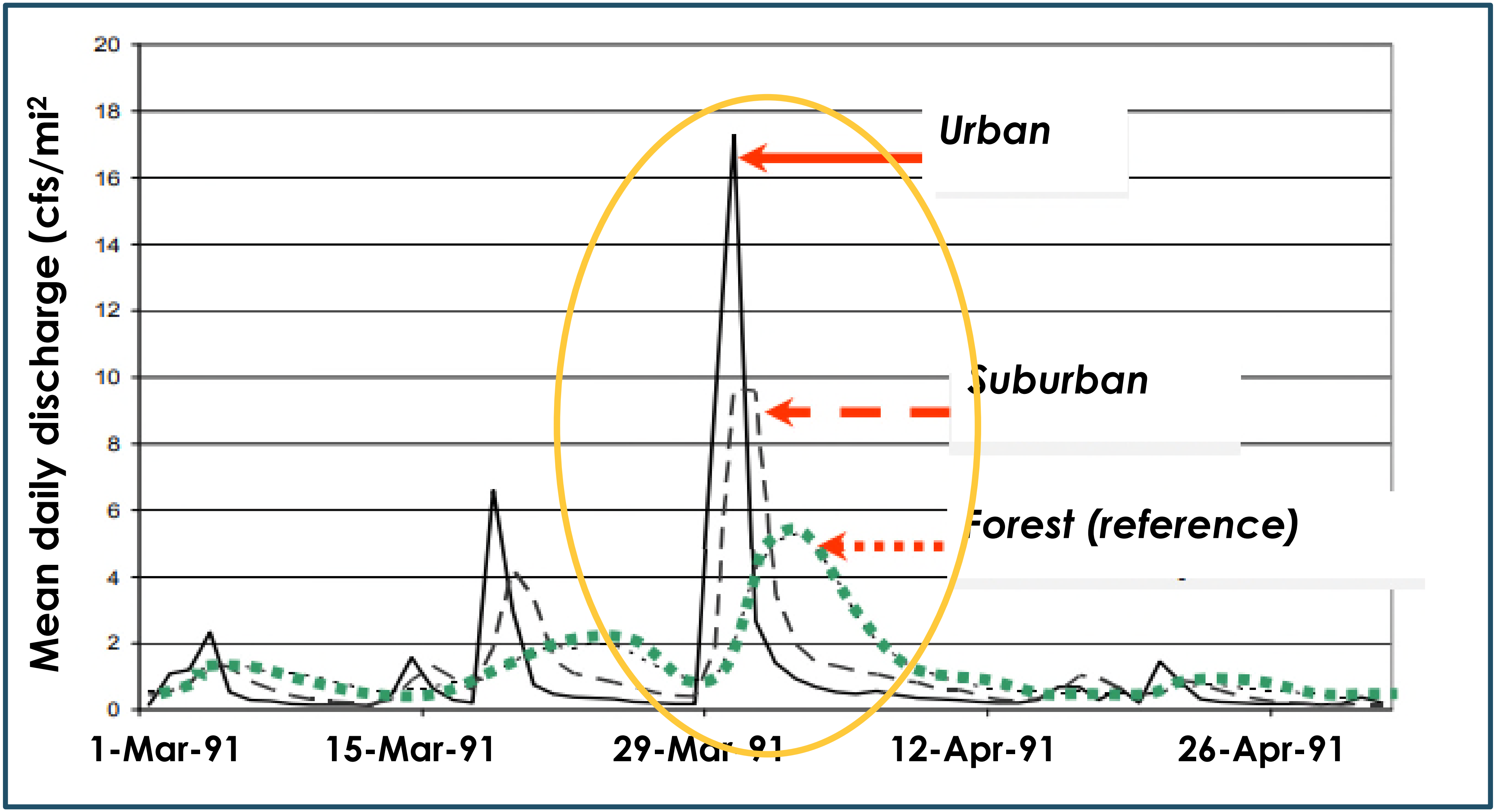
- Graphical plot of watershed response to rainfall
- Basis for predicting runoff to rainfall relationship



Hydrographs

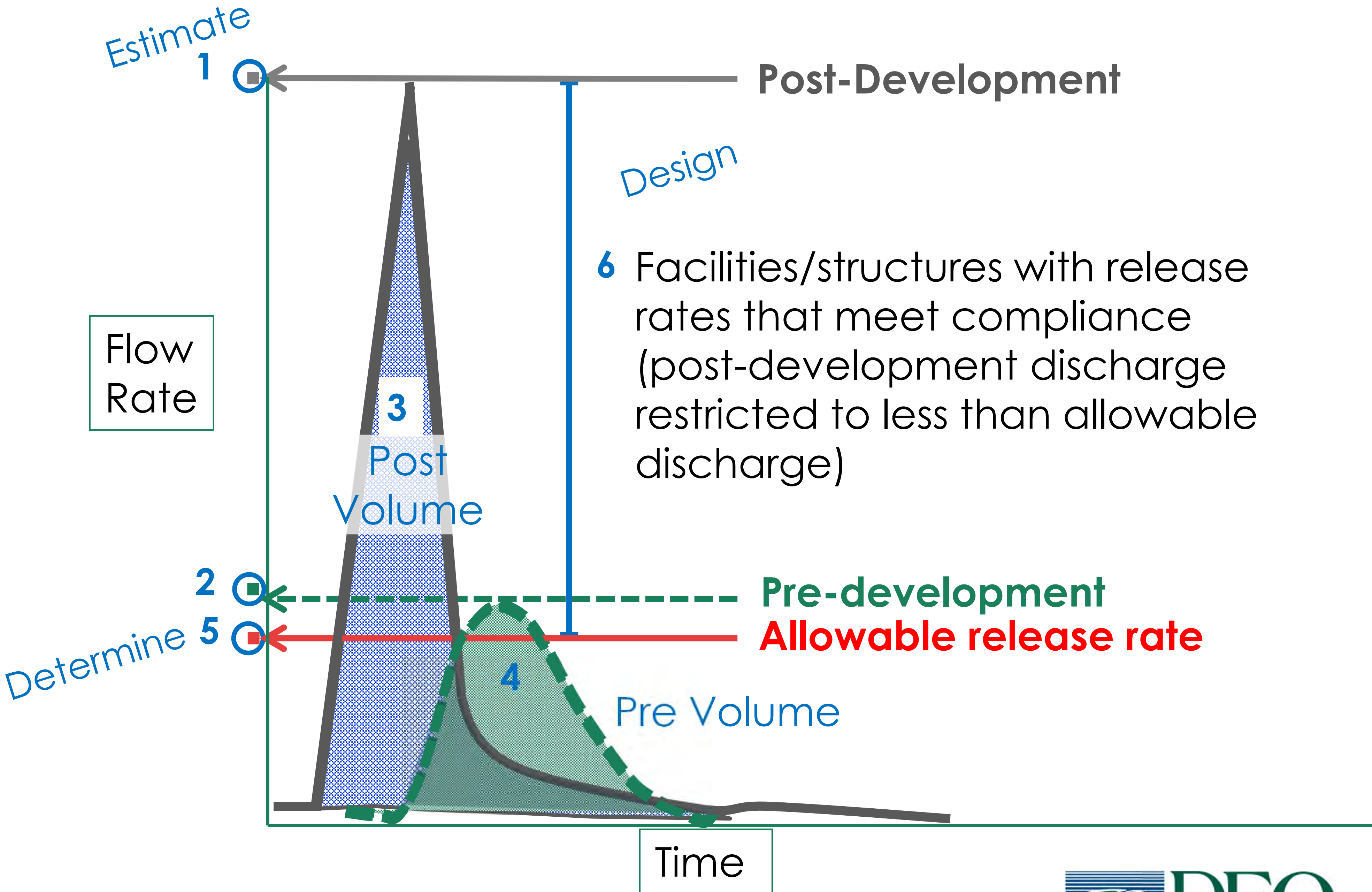


VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY



Normalized mean daily discharge for three gauging stations in the Chickahominy River watershed, Virginia from Focazia and Cooper, 1995 (Barten, 2013)

Managing Stormwater



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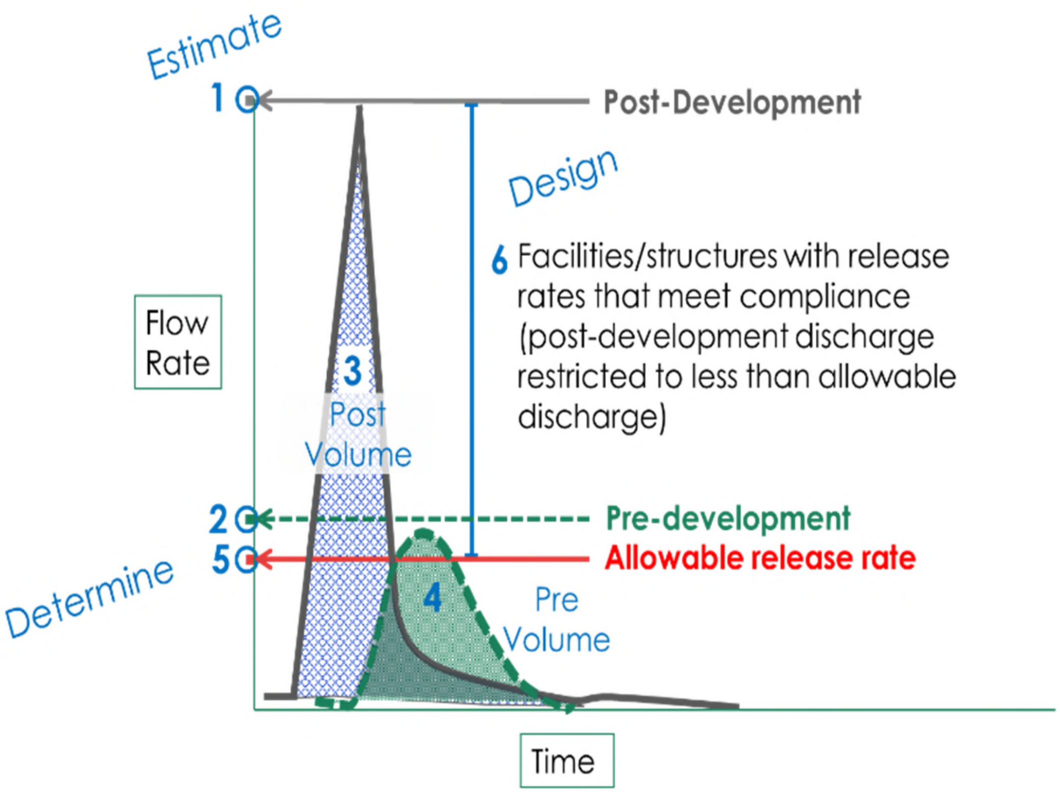
Managing Stormwater



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)

Approaching water quantity compliance

Inputs

- Rainfall (NOAA Atlas 14)
- Drainage area (reading topos)
- Watershed characteristics (coefficients, land cover, soil)
- Time of concentration

Runoff estimates

- Estimate pre-development runoff flows, volume, hydrograph
  - Determine allowable release rates
- Estimate post-development runoff flows, volume, hydrograph

Route/Design

- Estimate storage requirements/preliminary sizing to meet allowable release rates
- Route hydrograph through drainage system and/or facility
  - Route post-development hydrograph (inflow)
  - Produce outflow hydrograph (discharge)
- Refine design (facility/control structures)
  - Iterative process of design/routing to meet compliance

Module 9d.

Estimating Runoff

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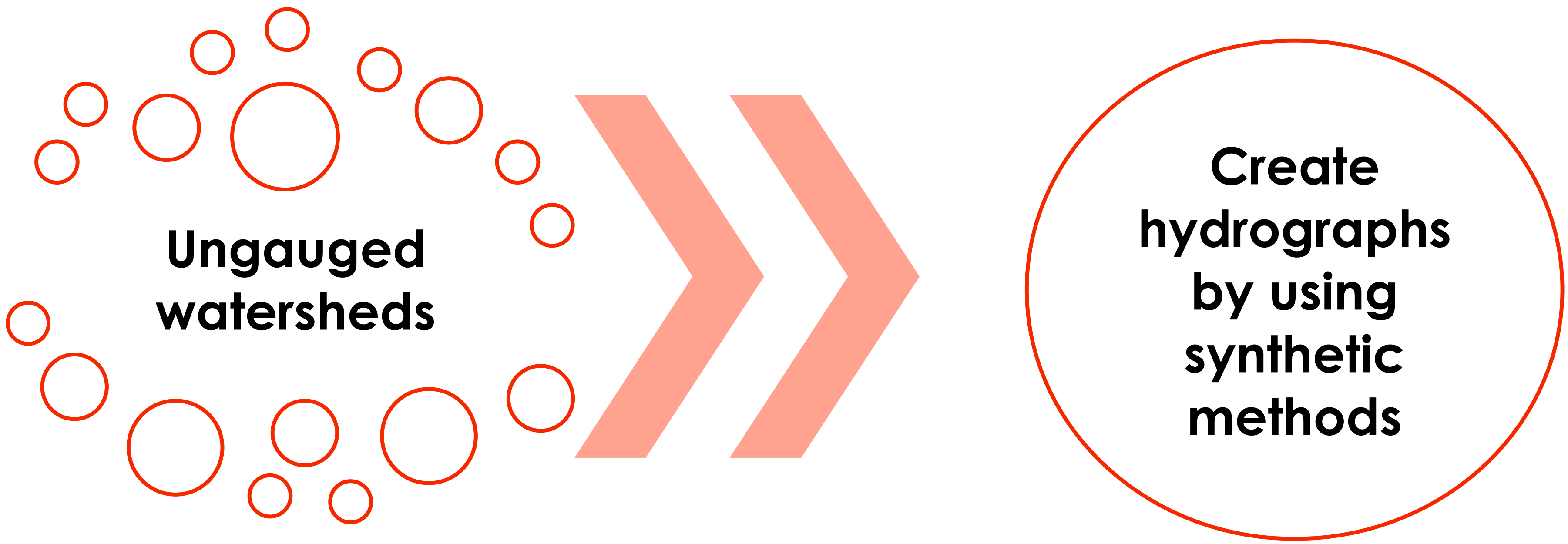
Estimating Runoff



Impossible to collect data at every discharge point of interest

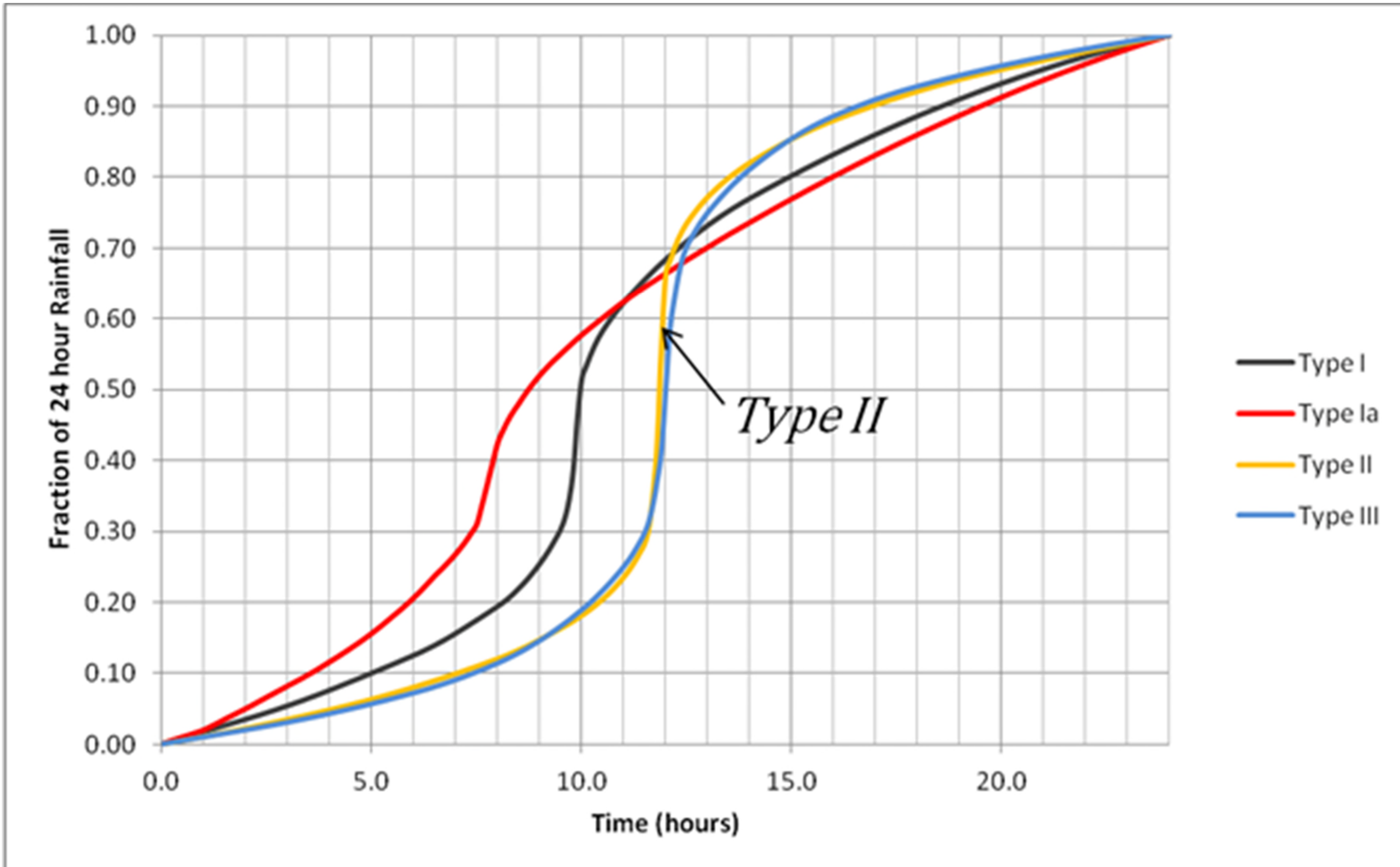
Each method limited in specific runoff parameters it can provide

Estimating Runoff

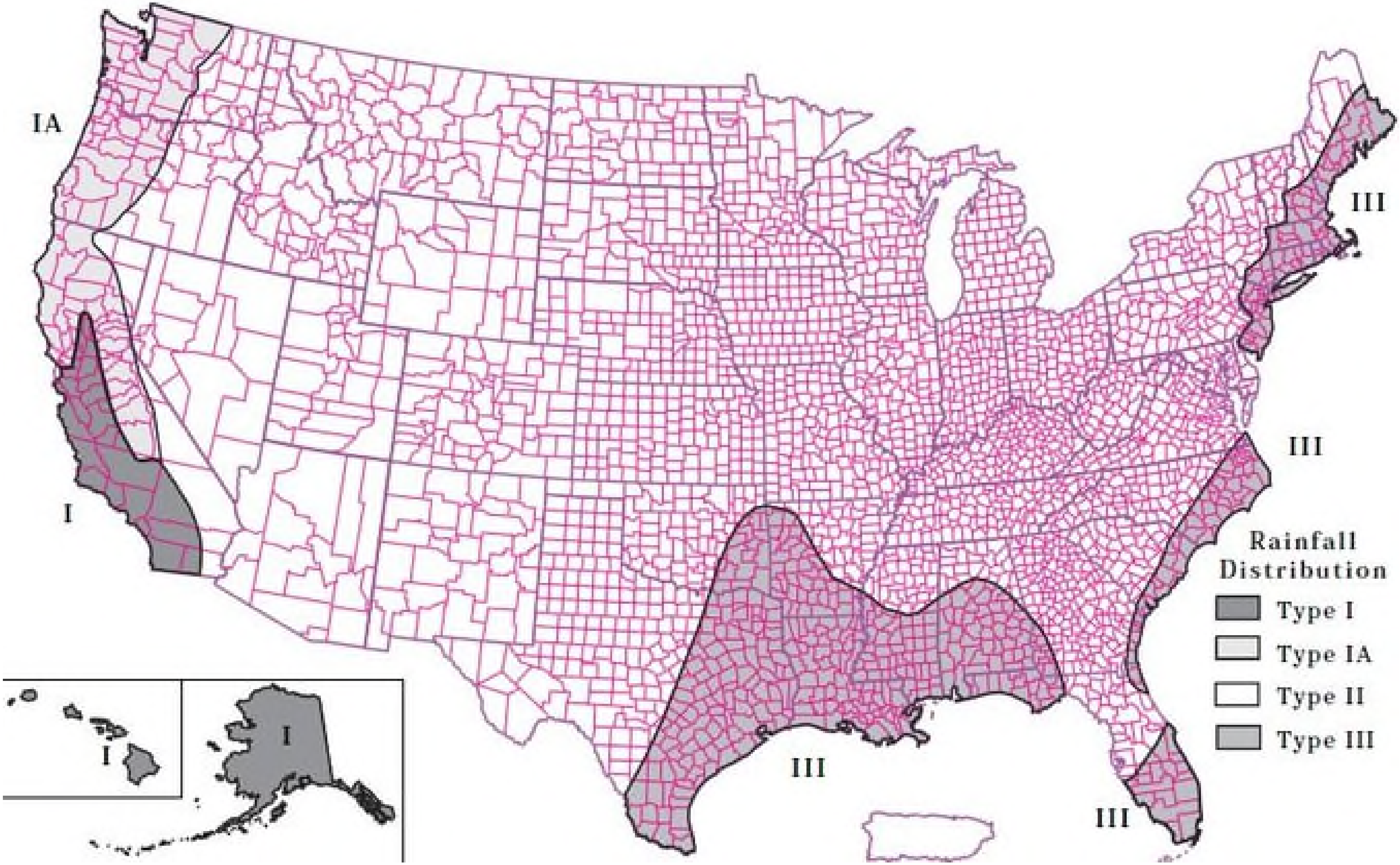
Inputs

- Rainfall (NOAA Atlas 14)
- Drainage area (reading topos)
- Watershed characteristics (coefficients, land cover, soil)
- Time of concentration

Synthetic Rainfall Distributions



Synthetic Rainfall Distributions



Synthetic Rainfall Distributions

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Rainfall Data Sources

- Technical Paper 40 (TP40)
  - Historical rainfall data through 1958
- NOAA Atlas 14
  - Updated rainfall data through 2000
  - Updated in 2004 and 2006 for Virginia
  - VESM regulations require NOAA Atlas 14 data for SWM computations and modeling

NOAA Atlas 14

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).

NOAA Atlas 14 - Virginia

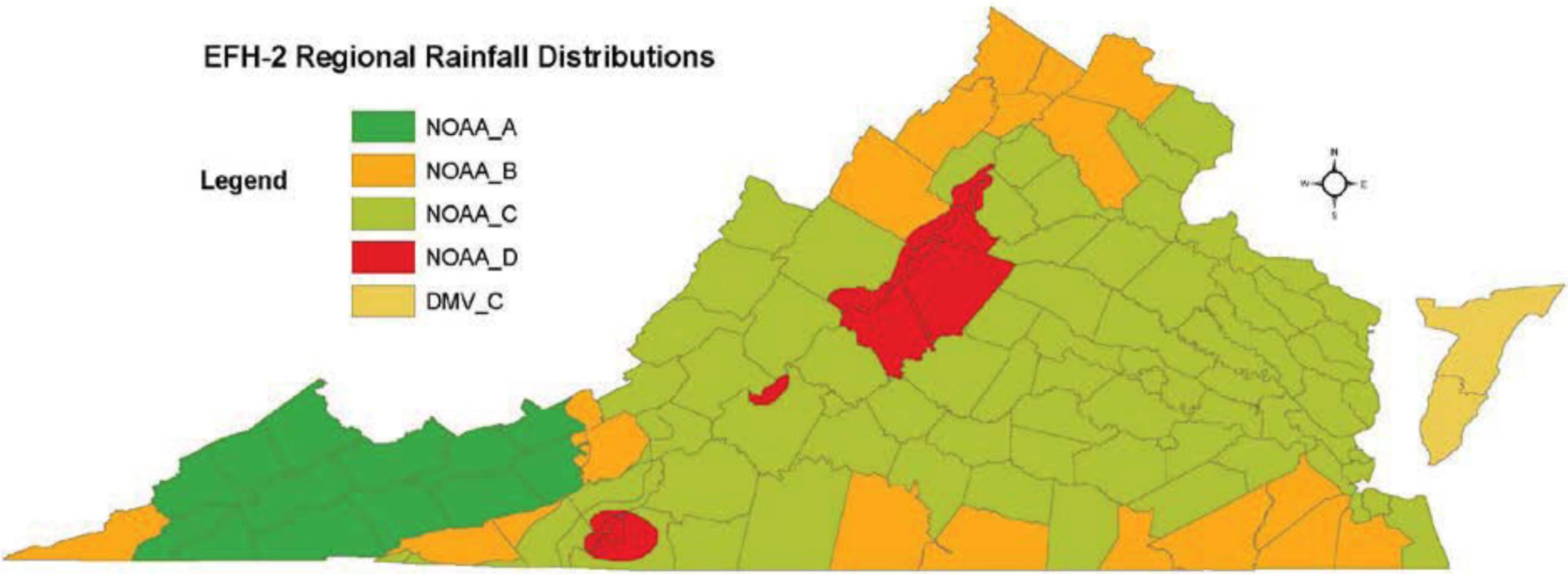

Figure 9-9. Rainfall Distribution Types for Virginia (210-VI-NEH, Amend. VA4, August 2012)

NOAA Atlas 14

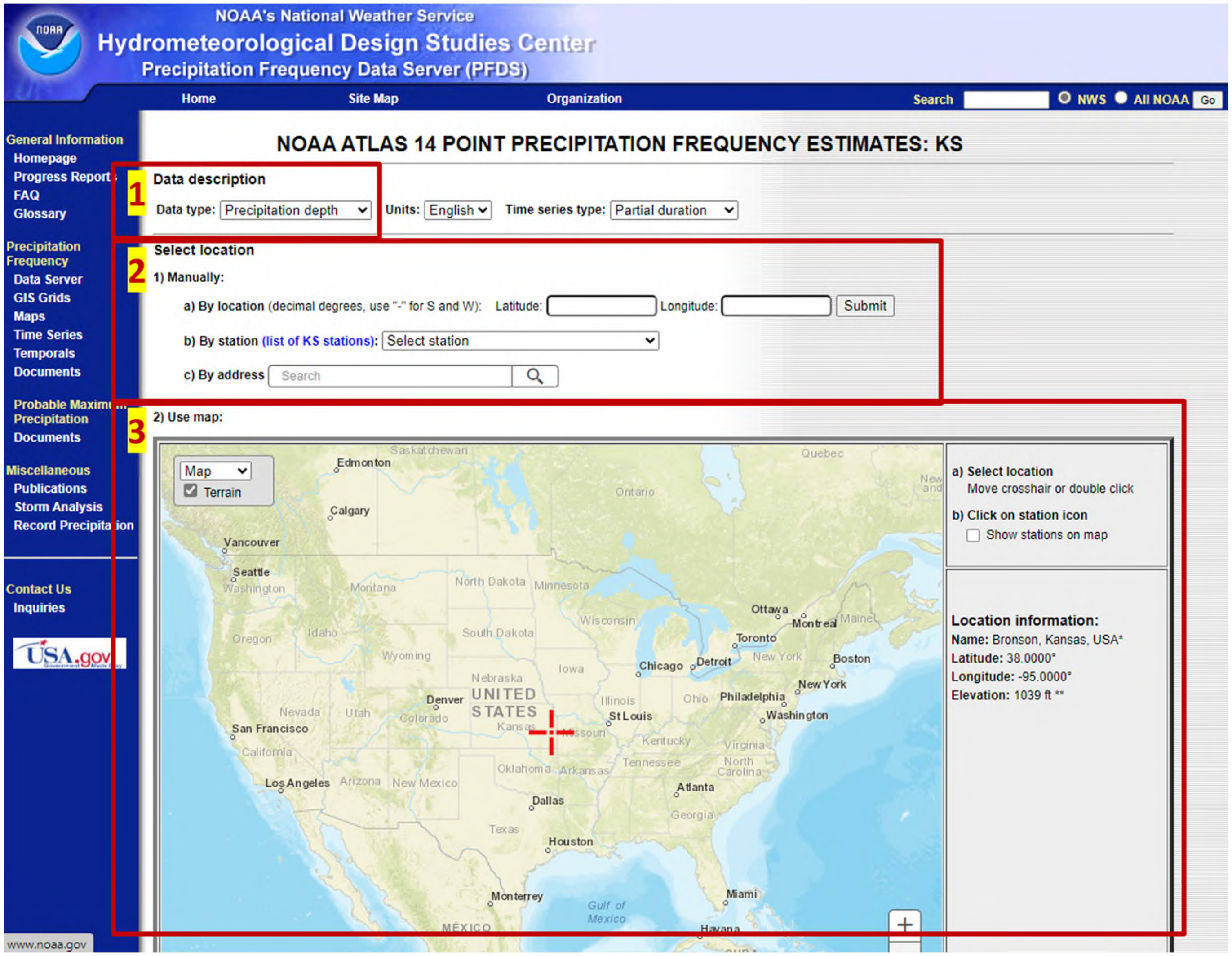

Figure 9-13. NOAA Atlas 14 Homepage

NOAA Atlas 14

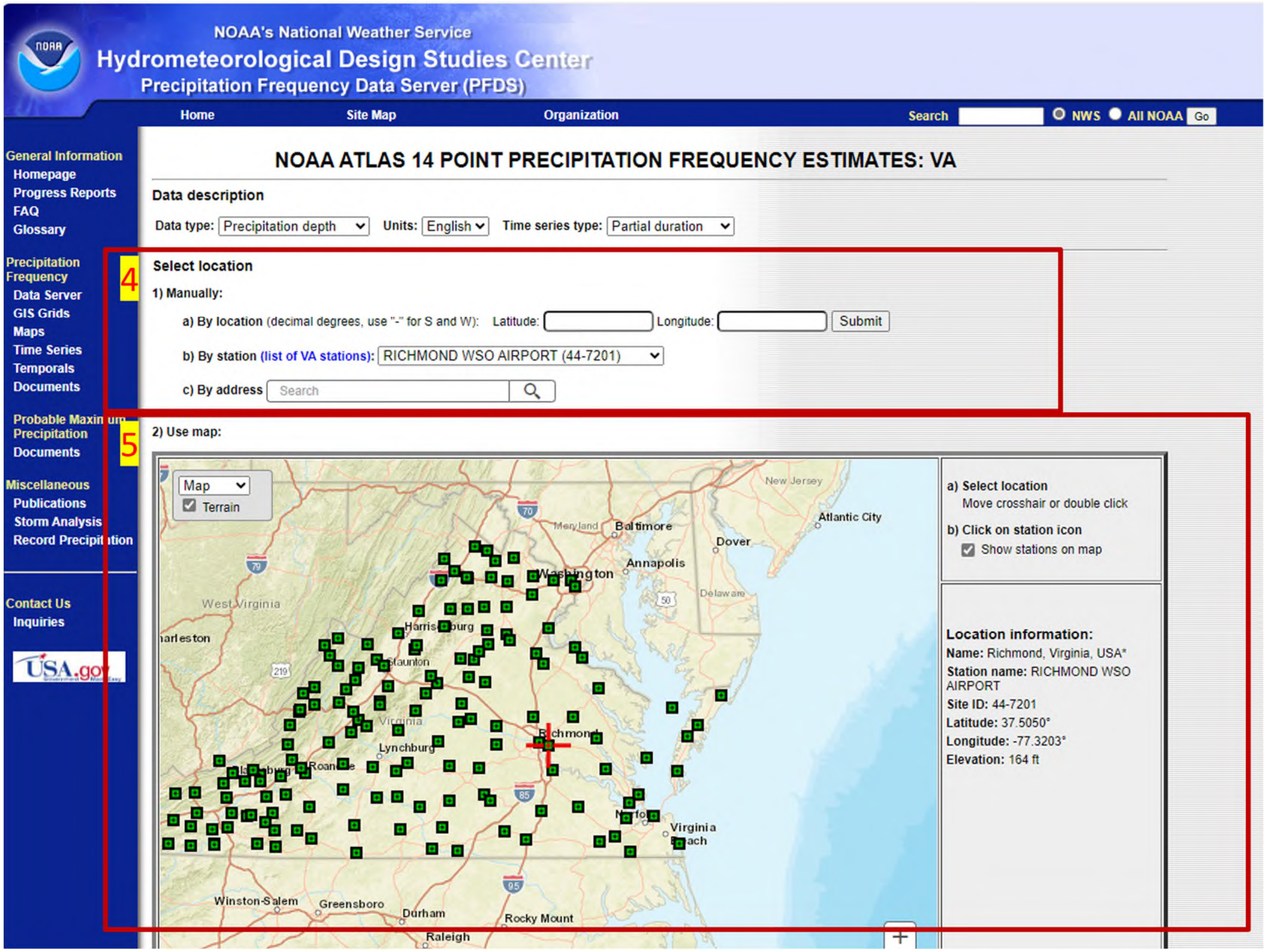

Figure 9-14. NOAA Atlas 14 Stations

NOAA Atlas 14

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

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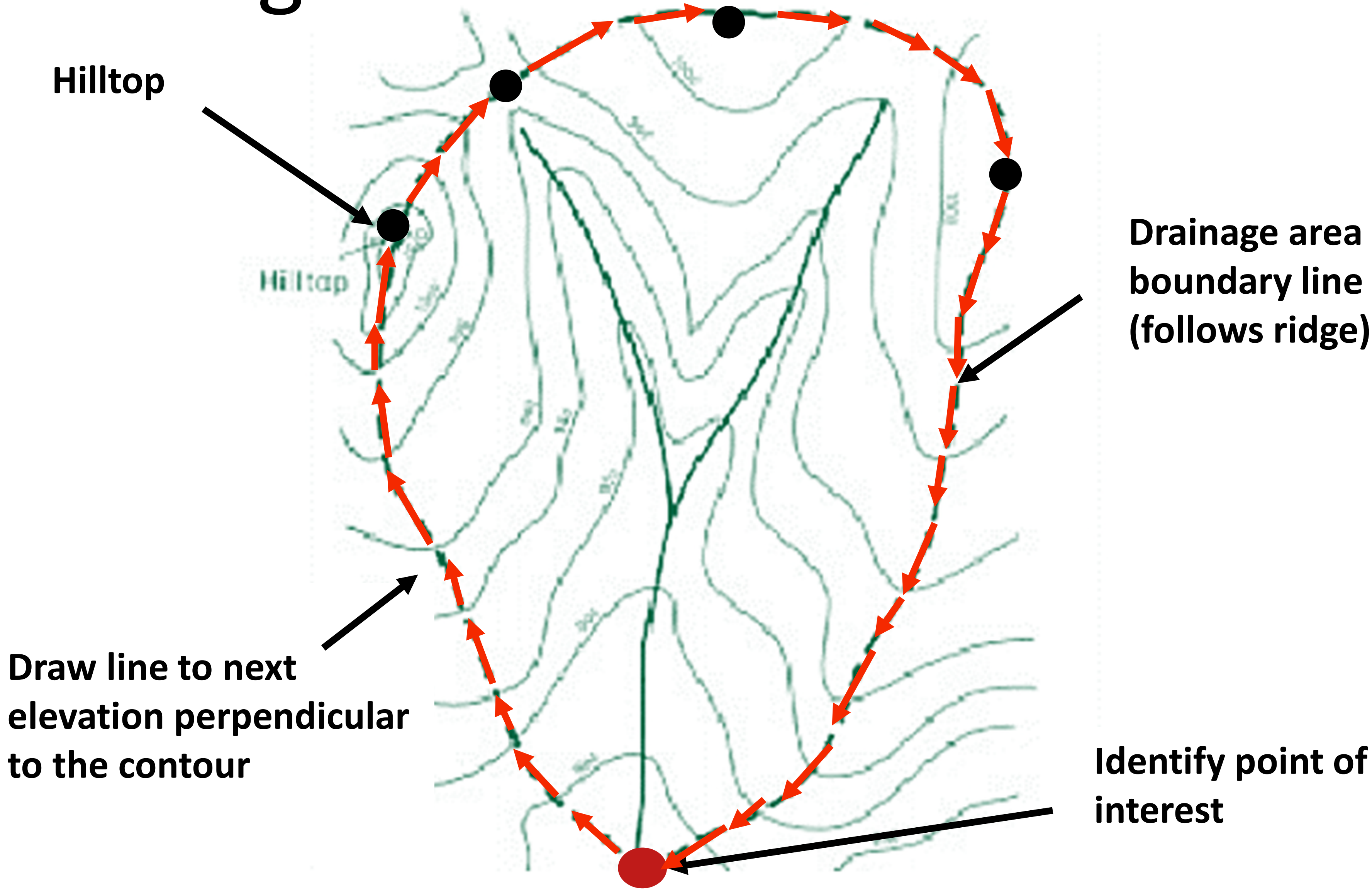
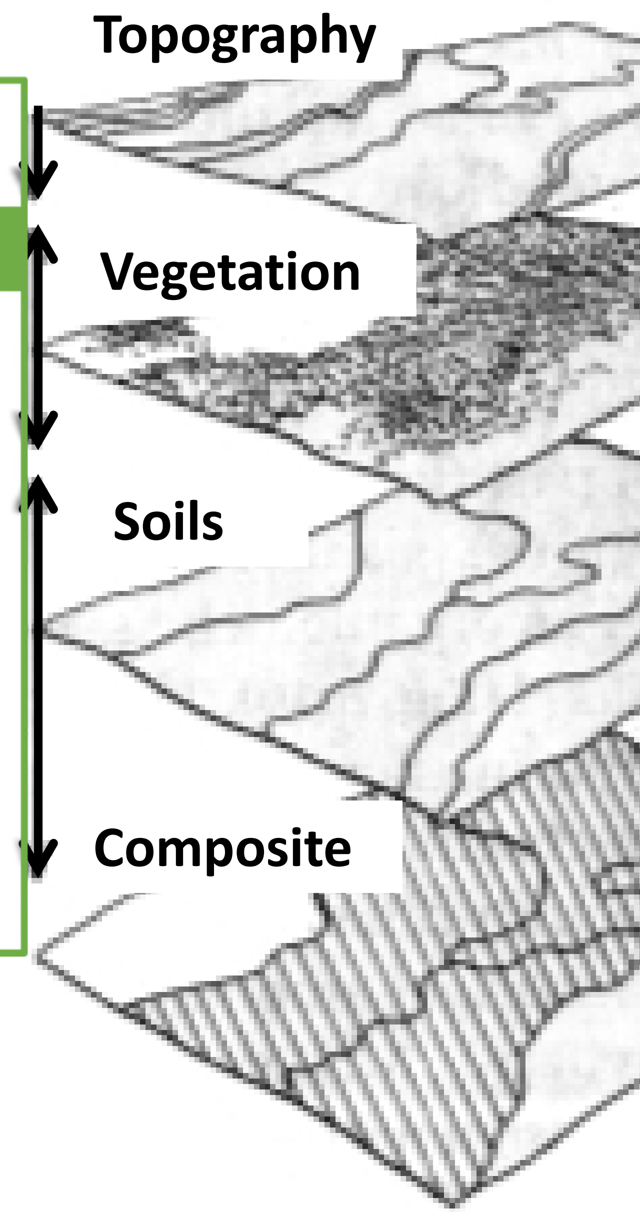
Drainage Area Delineation



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



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Time of Concentration

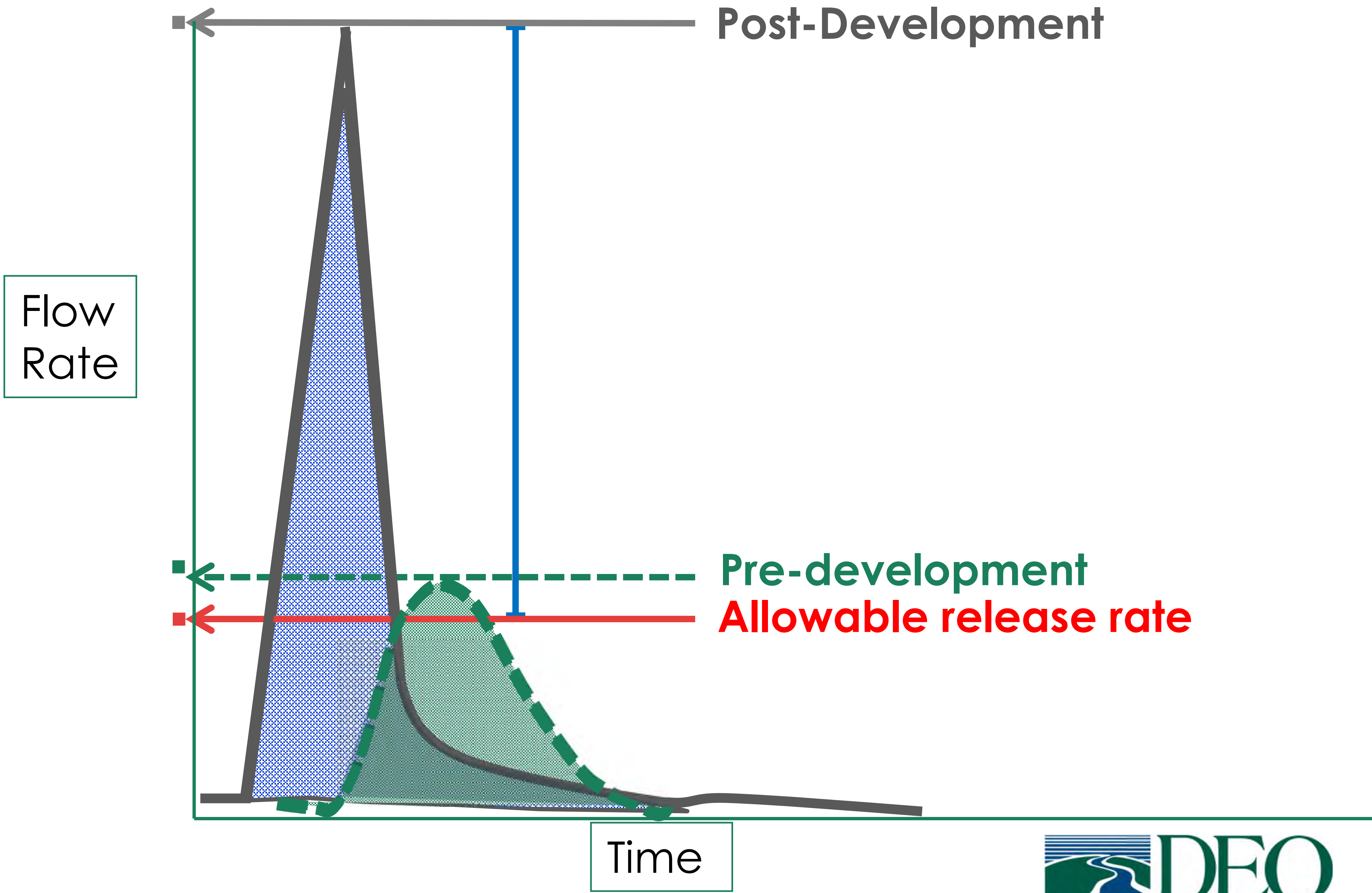
- Time for water drop to travel from hydraulically most distant point to outlet
- Several different methods

Time of Concentration

- Relates discharge to watershed characteristics
- Varies with watershed characteristics
  - Slope
  - Roughness
  - Flow patterns
- Needed to determine peak discharge for watershed

Time of Concentration

Which hydrograph has longer Tc?

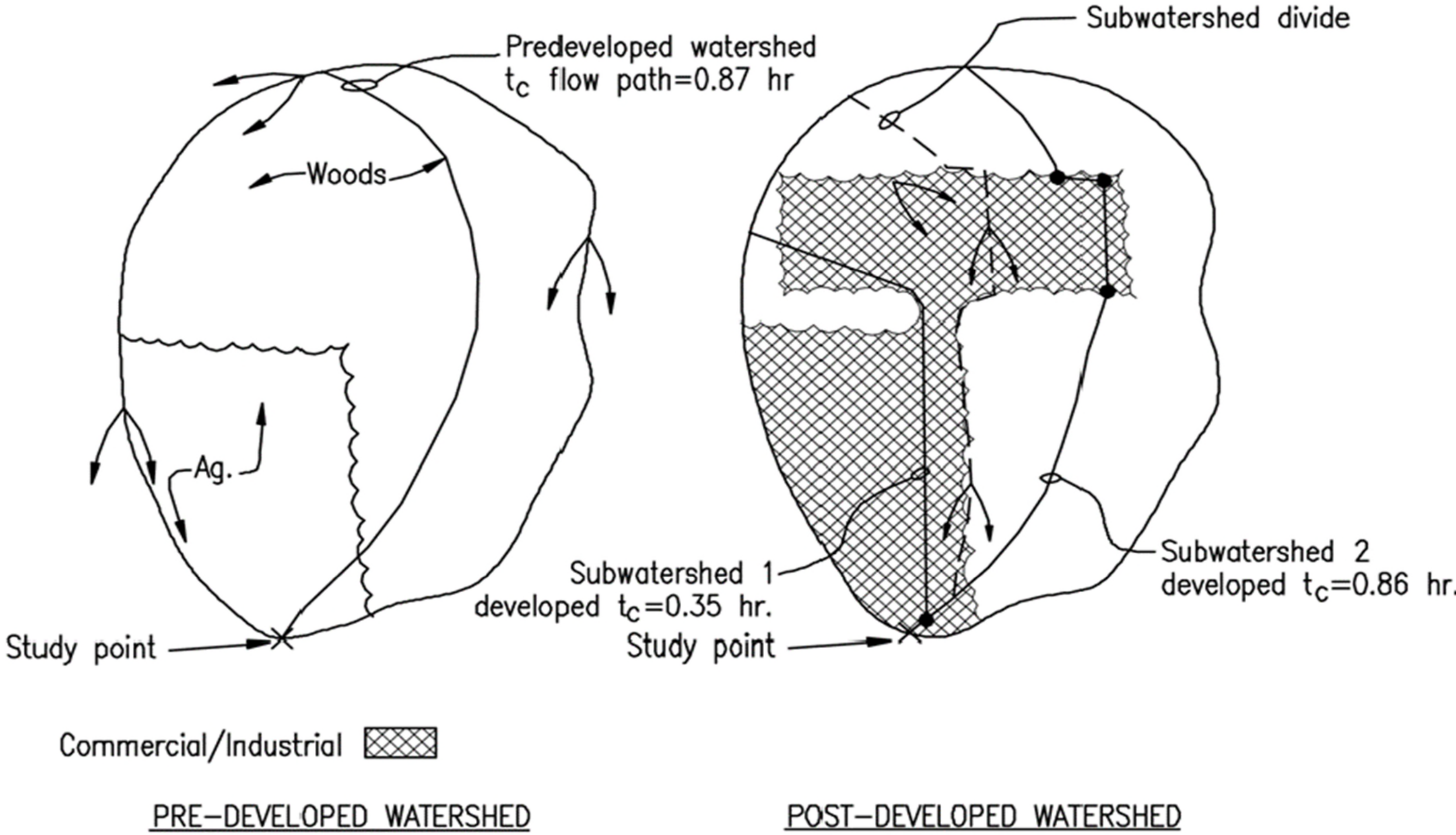


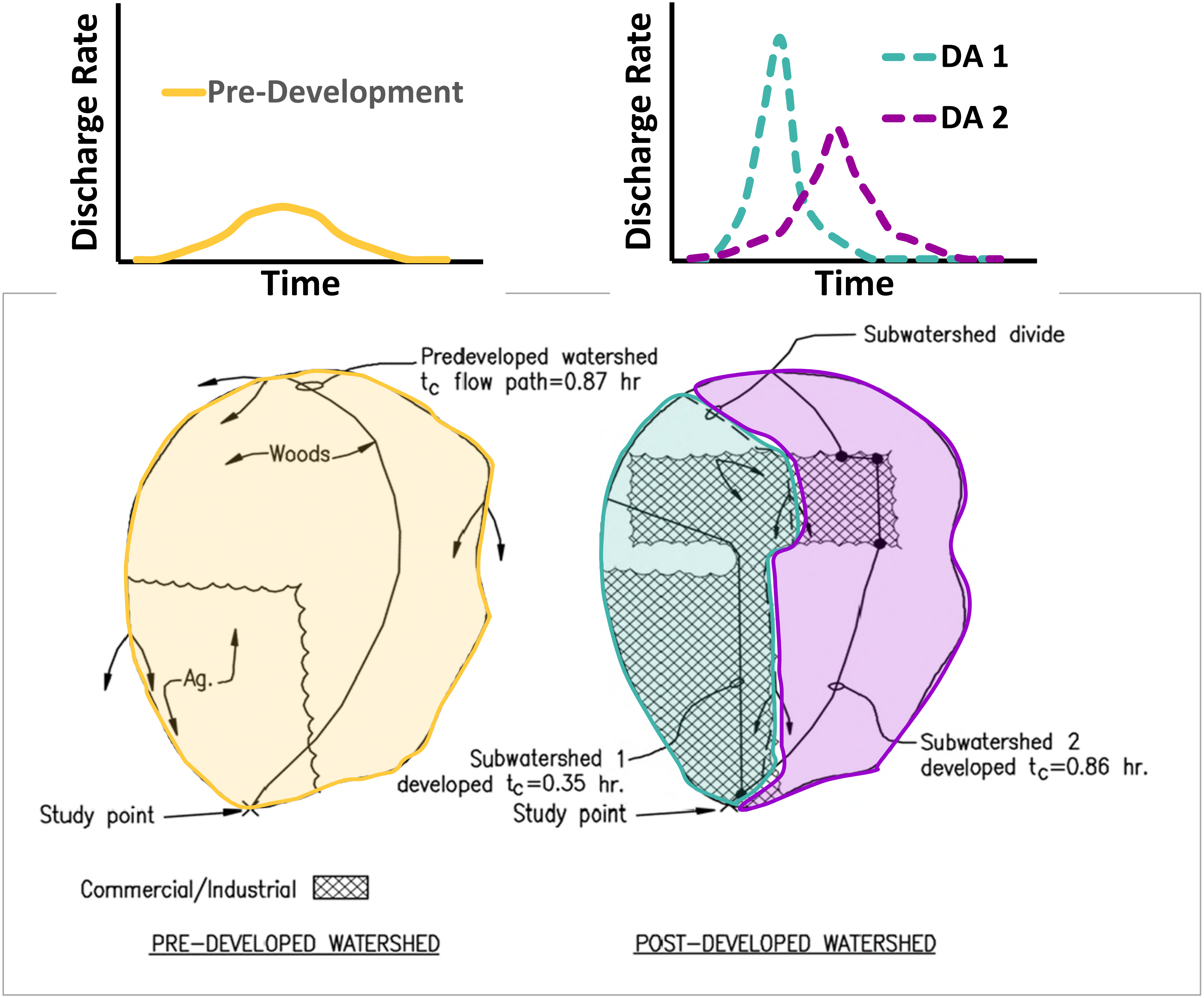
Time of Concentration

- Tc flow path should be representative of overall drainage area
- Multiple drainage areas to common discharge point should have Tc per drainage area
  - added via adding hydrographs (eg. WinTR-55, TR-20)

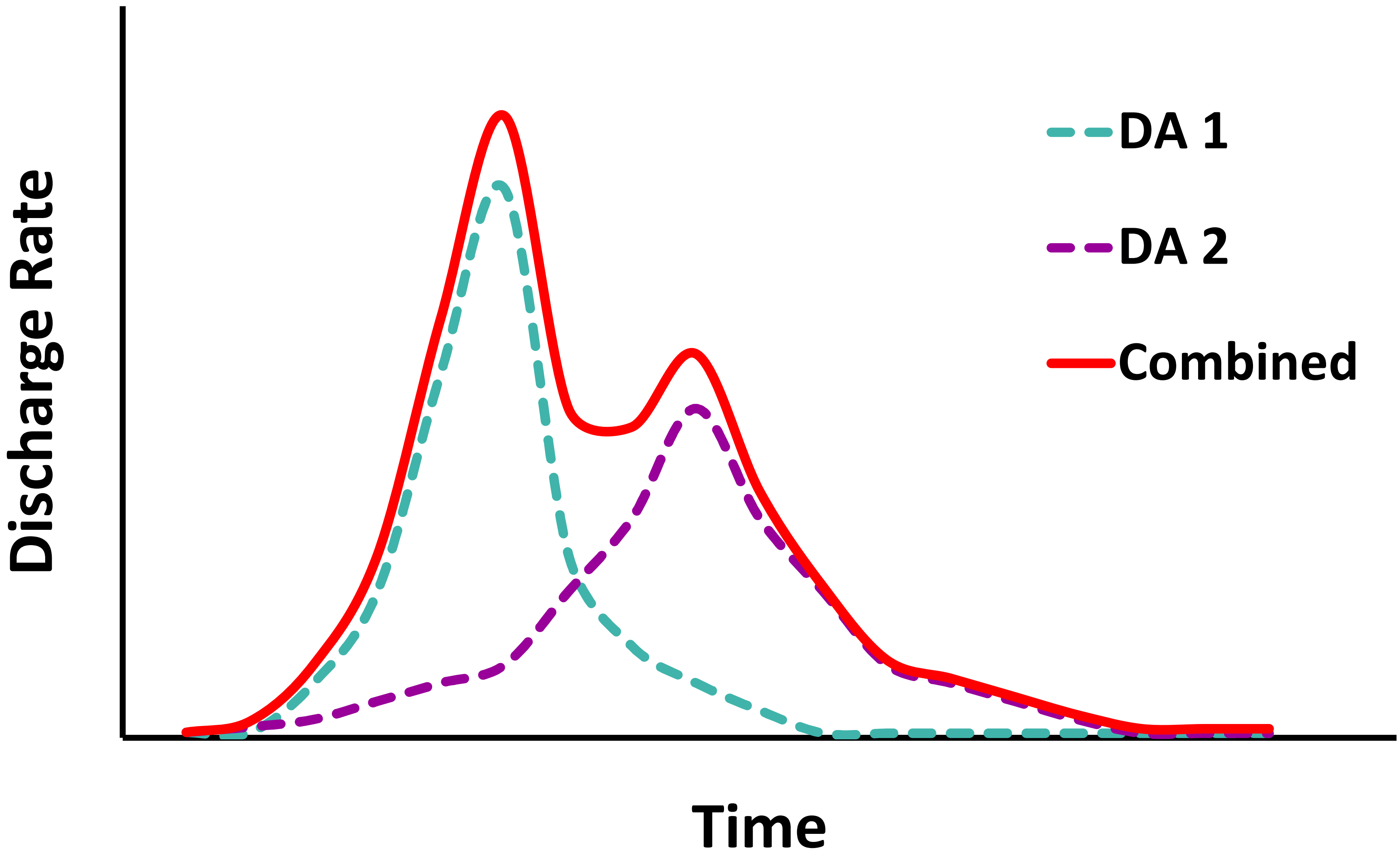
Time of Concentration (Tc) - VSWHB

- ‘hydraulically most distant’ point
- flow path most representative of drainage area (and drainage area peak flow)




Discharge Rate
Pre-Development
Time
Discharge Rate
DA 1
DA 2
Time
Predeveloped watershed
tc flow path=0.87 hr
Woods
Ag.
Study point
Commercial/Industrial
PRE-DEVELOPED WATERSHED
Subwatershed divide
Subwatershed 1
developed tc=0.35 hr.
Study point
Subwatershed 2
developed tc=0.86 hr.
POST-DEVELOPED WATERSHED

Cumulative hydrograph would need to be computed which takes into account the peak flow rates and timing for each sub-drainage area.



Time of Concentration

- 3 common methods:
  - Watershed Lag Method
  - Kirpich Method
  - TR55 Velocity Method

Time of Concentration (Tc)

Watershed Lag Method

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

(See NEH Chapter 15, 2010)

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

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

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Time of Concentration (Tc)

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.

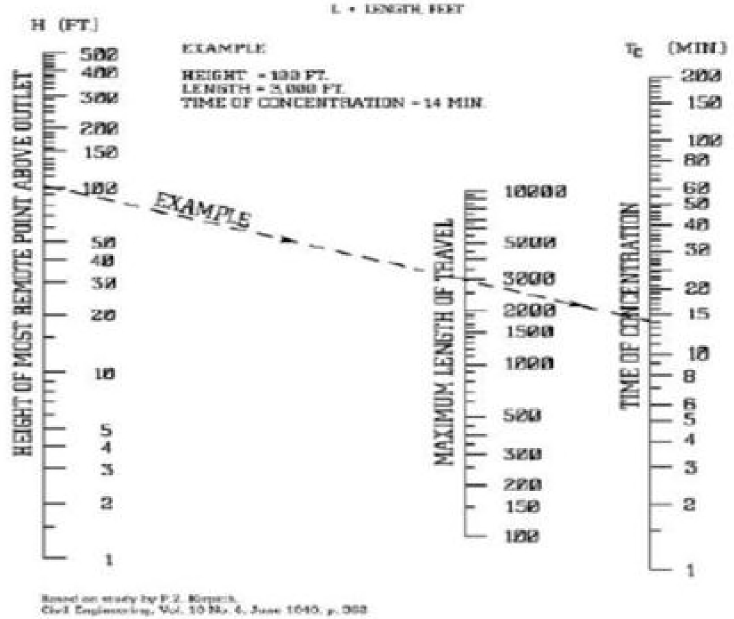
****Kirpich Chart should only be used for channel time in Virginia.**

Chapter 6 - Hydrology

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

$$T_C = 0.00948\ H^{0.38}\ L^{1.15}$$

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



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.

1 of 1 *VDOT Drainage Manual*

Time of Concentration (Tc)

Travel time (T_t):

Time it takes water to travel from one location to another in a watershed

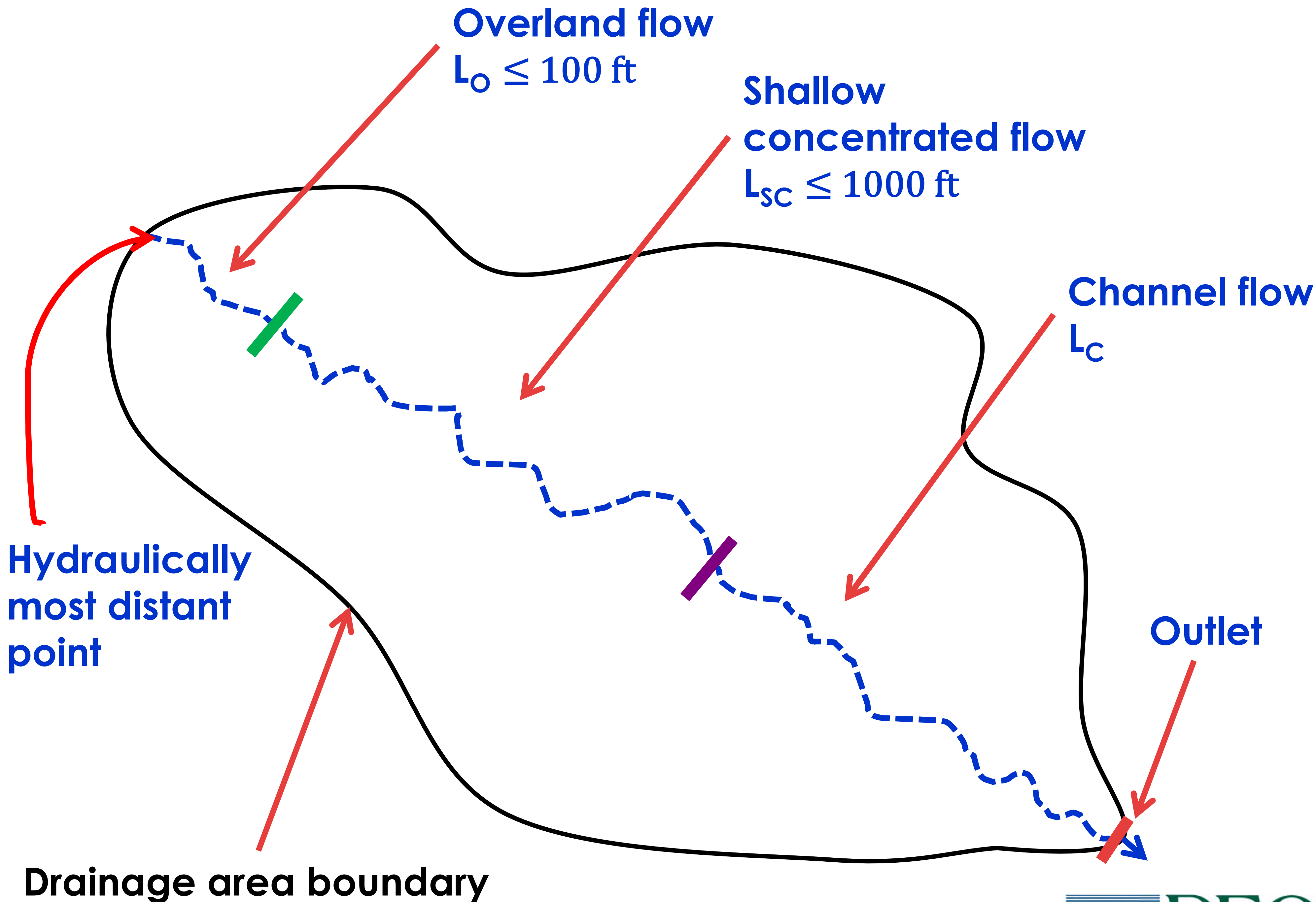
Time of concentration (T_c):

Time required for water to travel from most hydraulically distant point in watershed to point of analysis

(runoff from entire watershed contributing)

Sum of time increments for each flow segment

$T_c = \Sigma$ (overland flow + shallow concentrated flow + channel flow)


Overland flow
$L_O \leq 100$ ft
Shallow
concentrated flow
$L_{SC} \leq 1000$ ft
Channel flow
L_C
Hydraulically
most distant
point
Outlet
Drainage area boundary

Time of Concentration, Travel Time

Flow segments

Overland (Sheet) Flow **Manning's kinematic solution**	Shallow flow	Upper reaches of hydraulic flow path
Shallow Concentrated Flow **Graphical solution**	Overland flow converges to form defined flow	Flow Paths w/o defined channel
Channel Flow **Manning's Equation**	Flow converges in natural or manmade conveyances	Well defined drainageway

OVERLAND FLOW

- **Flow depth likely less than 0.05 feet, not greater than 0.1 feet**
- **Flow length - 100 foot maximum**
  - current WINTR55 documentation
  - NEH, 2010
  - DEQ policy

Overland Flow

- TR-55 and the Virginia Stormwater Management Handbook are both referenced in Part V, Article 3 of VESM regulations
  - The 1986 TR-55 guidance has been superseded by WinTR-55 as technical guidance

Overland Flow

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)

Overland Flow

NOTE:

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

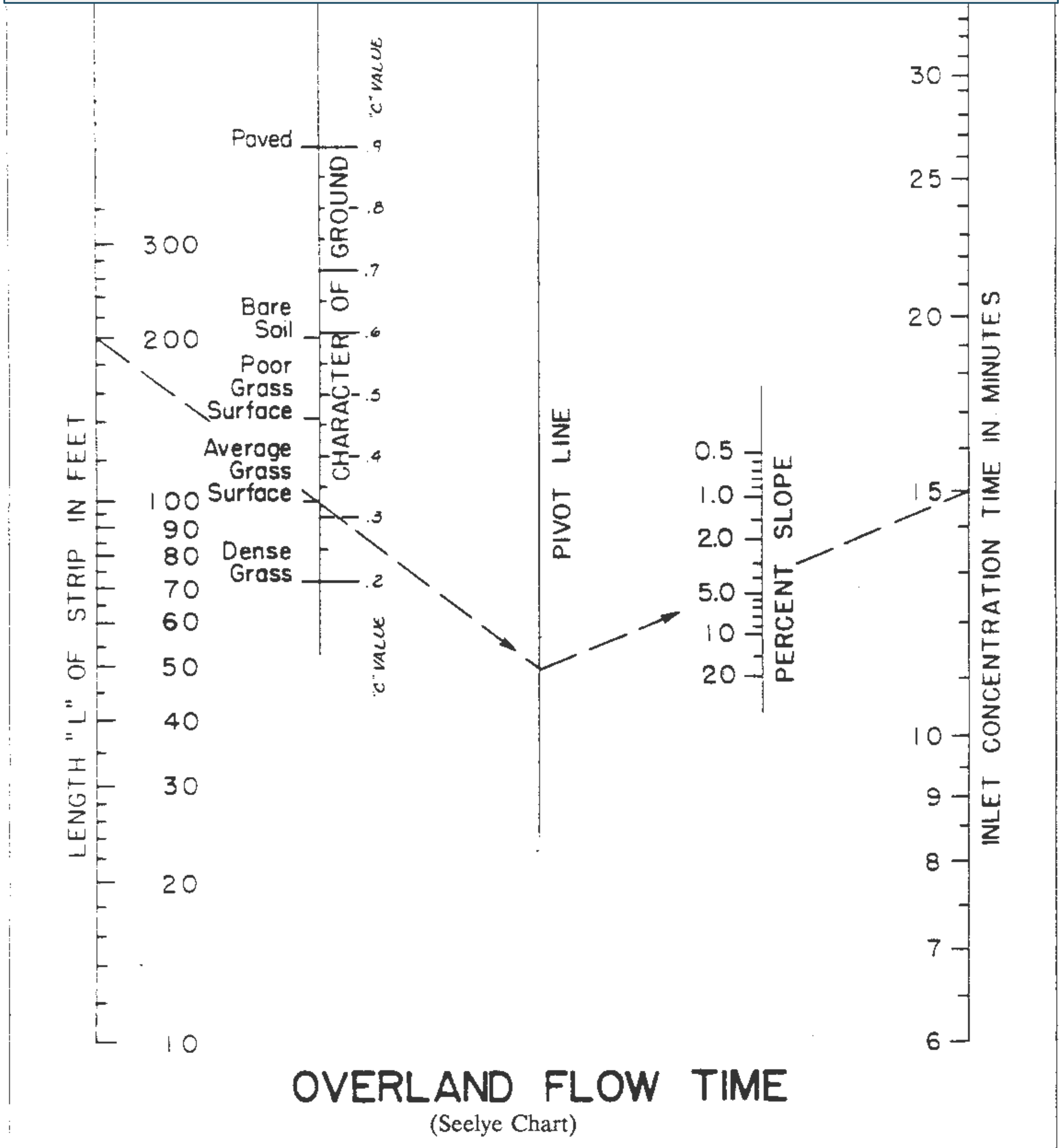
Time of Concentration (Tc)

- *Computing Overland Flow*
  - Seelye Method
  - Kinematic Wave Method
  - NRCS Technical Release 55 (TR-55) Method

- **Simplest method**
- **Small developments**

Page 44 of participant guide

Seelye Chart, VSWHB



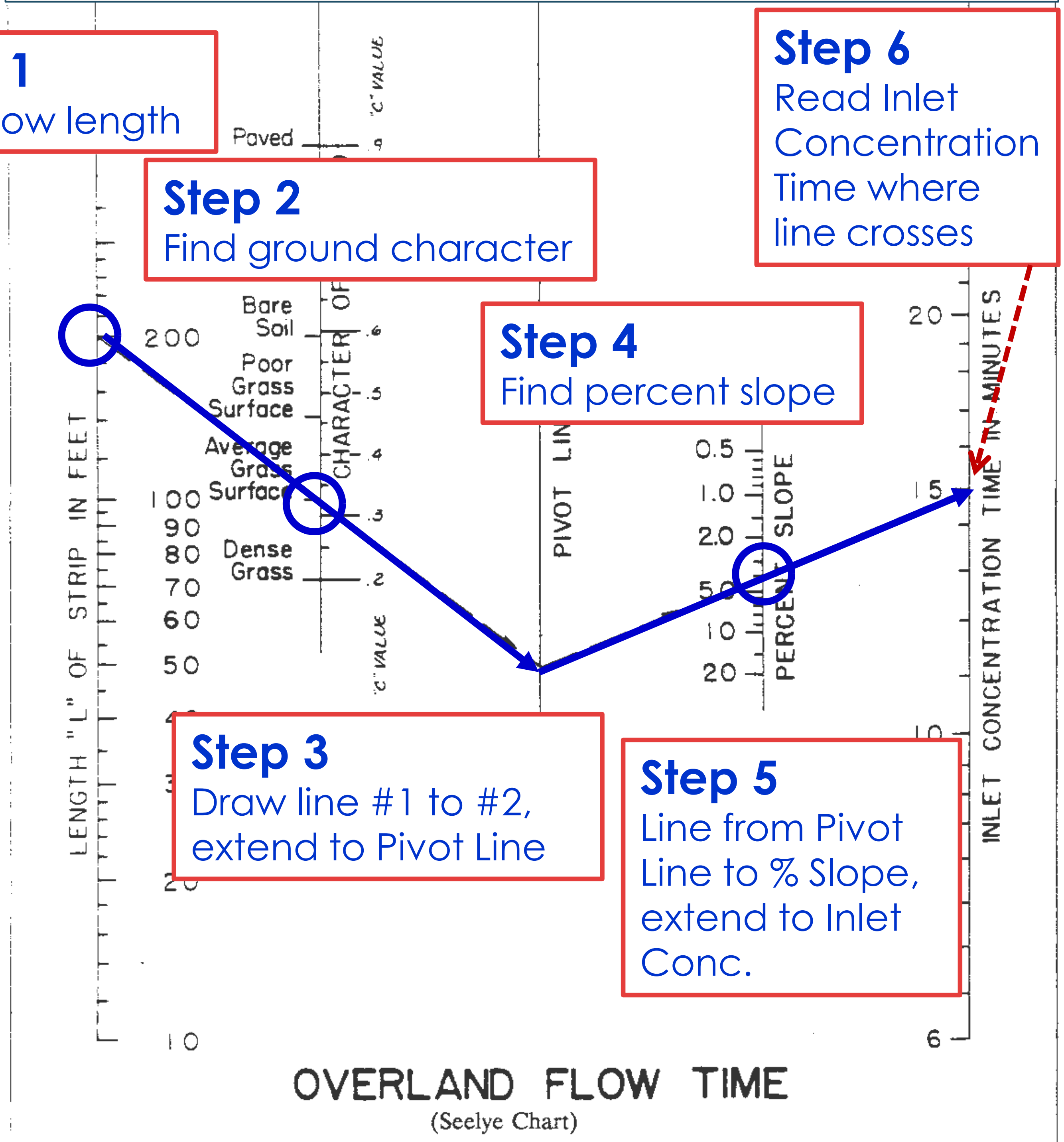
Example:

- 200 ft flow path
- Average Grass Surface ("C" value 0.32)
- 4% slope

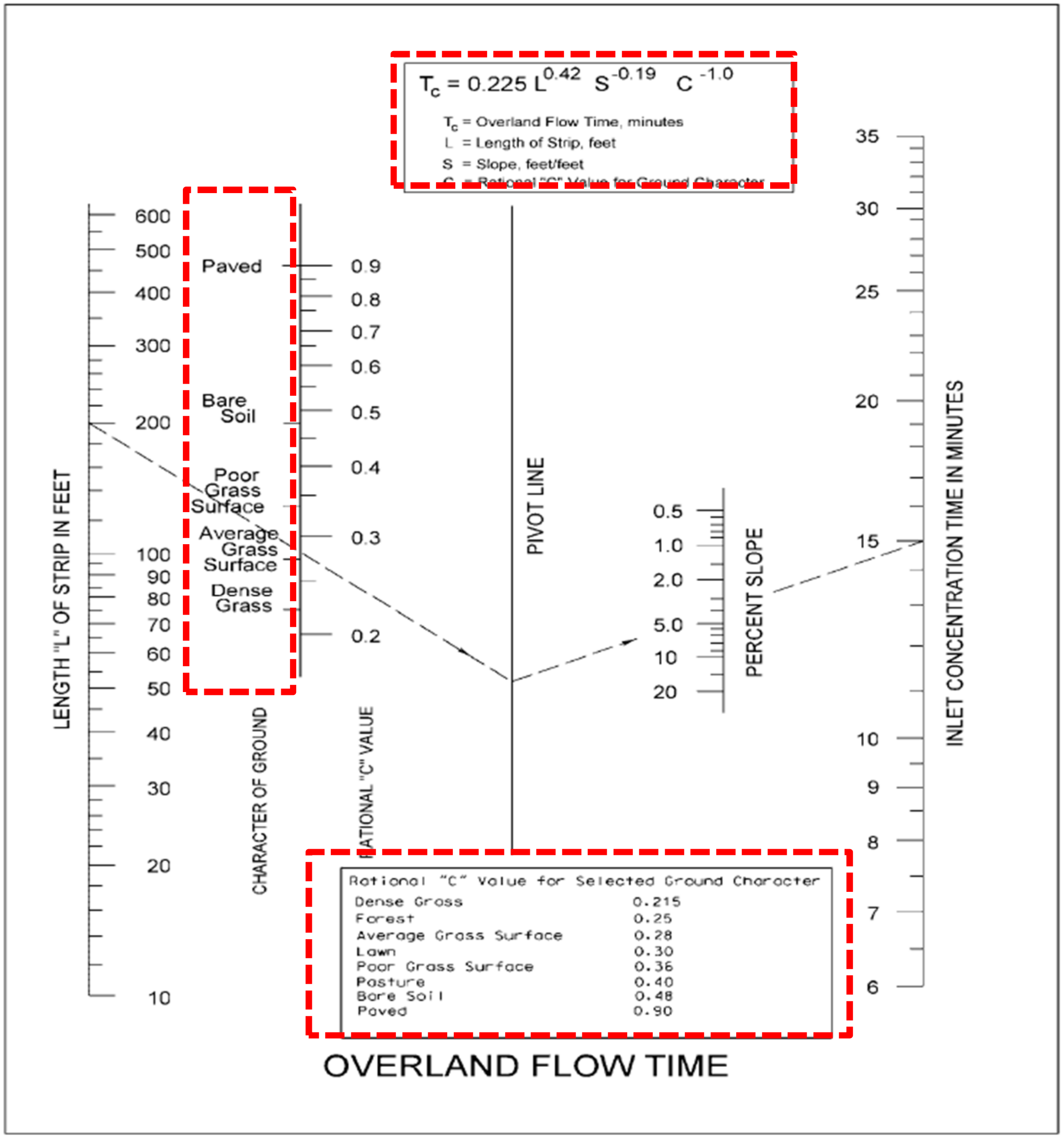
Answer:

***Tt* = 15 minutes**

Seelye Chart, VSWHB



VDOT



REPRINTED WITH PERMISSION FROM "DATA BOOK FOR CIVIL ENGINEERS" VOL. I - DESIGN
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

Overland Flow: Kinematic Wave Model

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

L = length of overland flow (feet)

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

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

S = slope (feet/feet)

VSWHB, Appendix A, Section A.3.2.3

Table A-1 Manning's Roughness Coefficients for Sheet Flow (flow depth generally ≤ 0.1 foot)

Land Cover	Manning's n
Smooth surface (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover: ≤ 20%	0.06
Residue cover: > 20%	0.17
Grass:	
Short-grass prairie	0.15
Dense grasses*	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods: **	
Light underbrush	0.40
Dense underbrush	0.80

Notes:

Source: NRCS National Engineering Handbook, Table 15-1

* Includes weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

** When selecting n, consider cover to a height of about 0.1 feet, as this is the only part of the plant cover that will obstruct sheet flow.

Overland Flow:
NRCS TR-55 Method

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

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)

Shallow Concentrated Flow

Occurs where overland flow converges to form small rills, gullies, and swales

Flow length 0 to 1000 feet maximum

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Shallow Concentrated Flow: NRCS TR-55 Method

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

L = flow length (feet)

V = average velocity (feet/second)

t = conversion factor: 3600 seconds/hr or 60 seconds/min.

Tc – Shallow Concentrated Flow

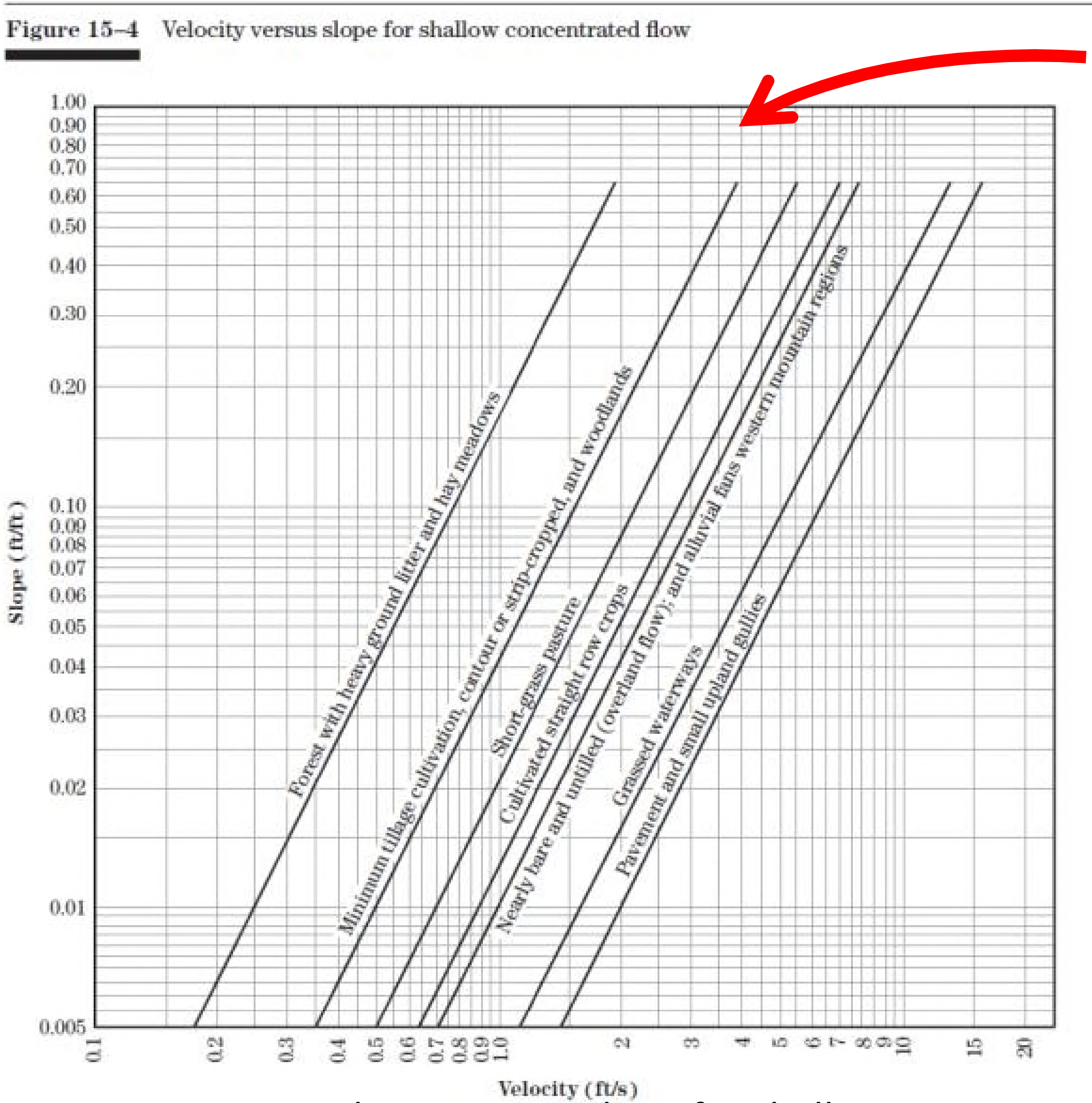


Figure 9-22: Velocity versus slope for shallow concentrated flow (TR-55, 1986)

1. Obtain velocity using slope and land cover
2. $$Tt = \left(\frac{L}{V \times t} \right)$$

L = flow length (feet)

V = average velocity (ft/second)

t = conversion factor

Tc – Shallow Concentrated Flow

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	$V = 2.516(s)^{0.5}$

- Can be used for slopes less than 0.005 ft/ft

Tc – Shallow Concentrated Flow

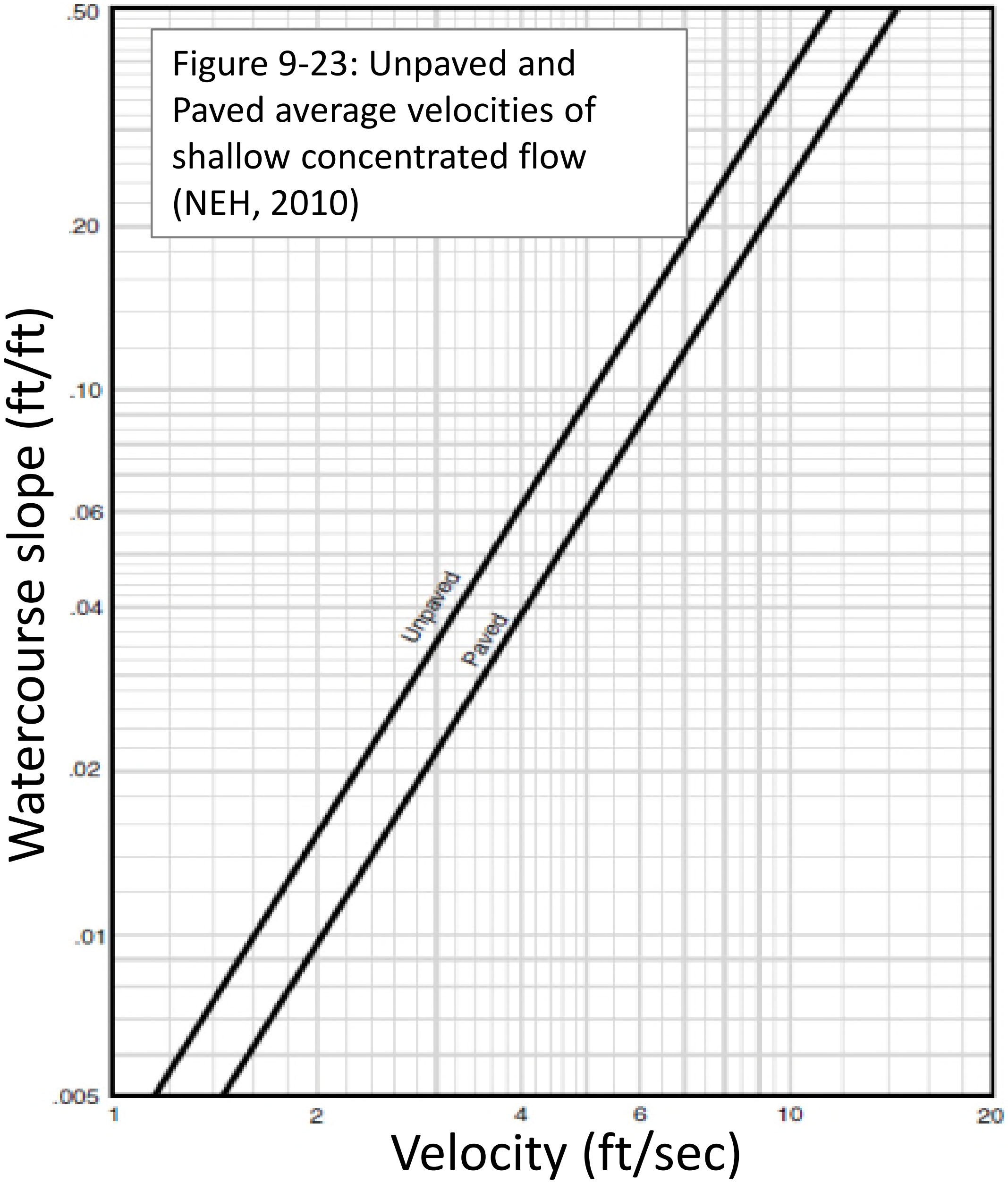
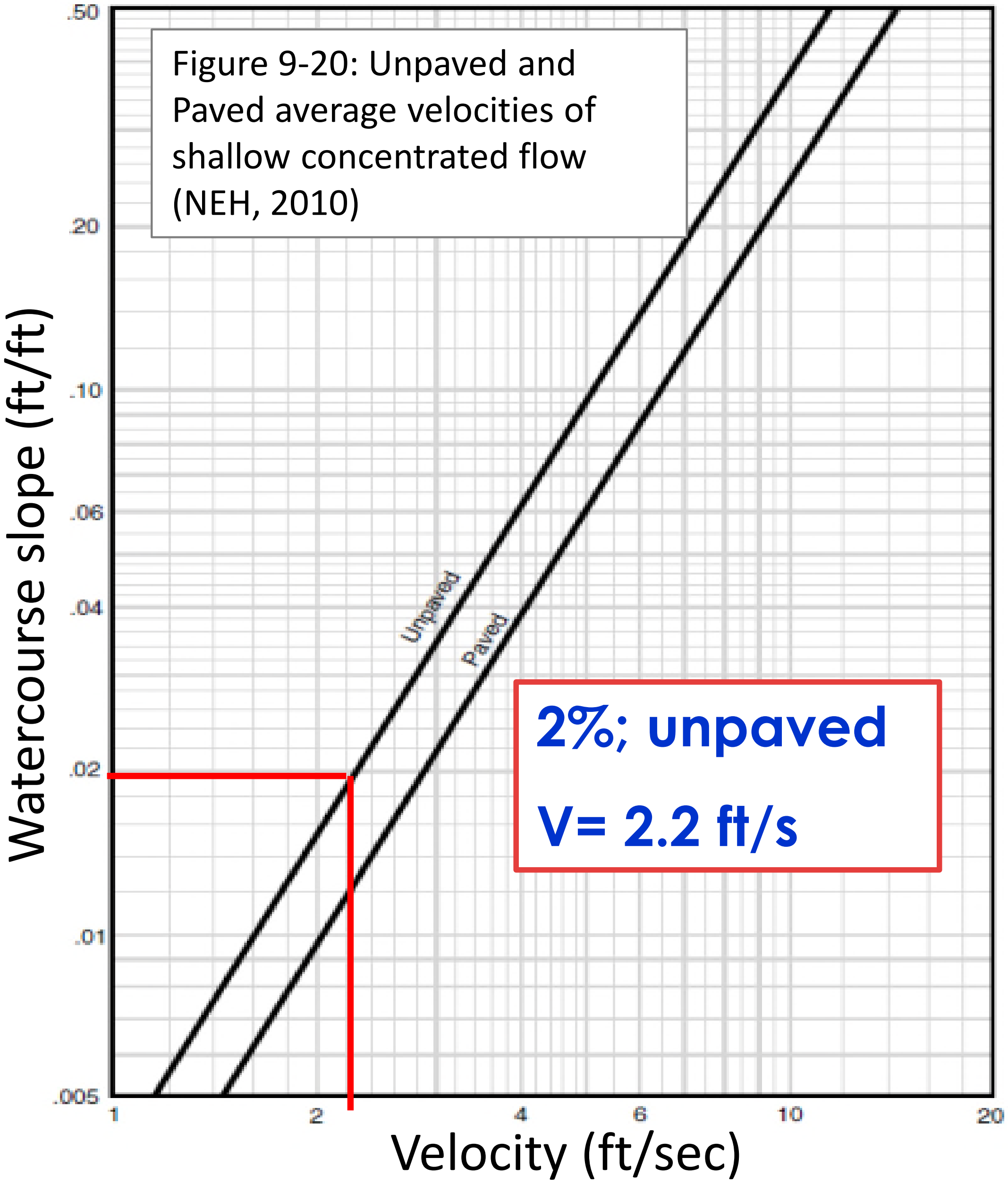


Figure 9-23: Unpaved and Paved average velocities of shallow concentrated flow (NEH, 2010)

Initial curves presented in TR-55 (1986)

Sufficient for urban

Tc – Shallow Concentrated Flow



Find travel time for:

500 ft shallow concentrated flow length over unpaved surface with 2% slope

$$T_t(hrs) = \frac{l}{3{,}600\ s/hr(V)}$$

$$= \frac{500ft}{60\ s/min(2.2ft/s)}$$

= 3.8 min.

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Tc – Shallow Concentrated Flow

Additional supplemental curves using assumptions for flow shape, width, depth

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

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

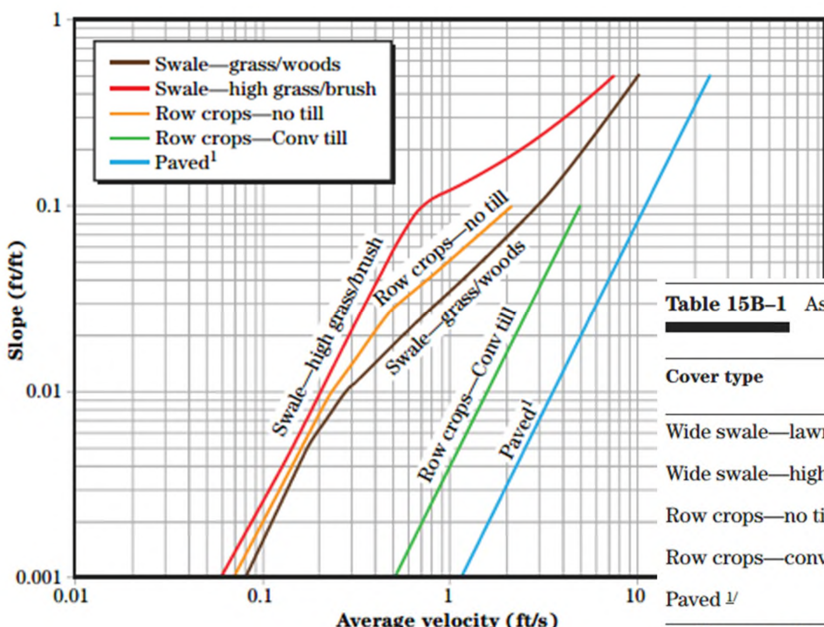

Table 15B–1 Assumptions used by Cerrelli and Humpal to develop shallow concentrated flow curves

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.

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Channel Flow

- Occurs where concentrated flow occurs in channels with well-defined cross-section (streams, ditches, gutters, pipes, etc.)
- Use velocity from Manning's equation for open channel flow:

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

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)

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

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

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 (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 CONCENTRATION 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

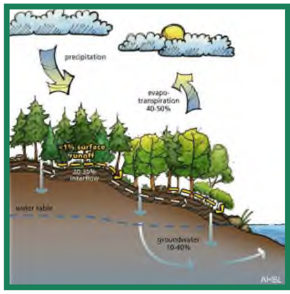
	Segment ID		
12. Cross sectional flow area, a .... ft^2			
13. Wetted perimeter, p_w .... ft			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r .... ft			
15 Channel slope, s .... ft/ft			
16. Manning's roughness coefficient, n			
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ....ft/s			
18.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

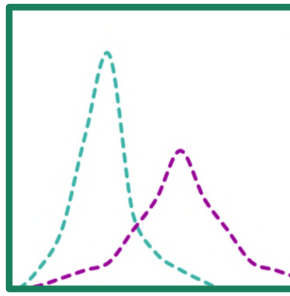
Time of Concentration Limitations

- Overland flow should not exceed 100 ft
- Storm sewers require careful identification of hydraulic flow path
- Culverts/bridges can detain runoff so routing may be required
- Minimum Tc used in TR-55 is 5 minutes (0.1 hr)

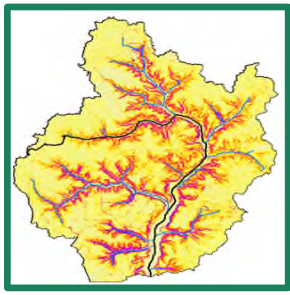
Q&A



Hydrologic Cycle



Understanding Hydrographs



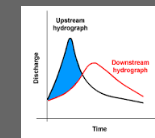
Time of Concentration

Overland, Shallow Concentrated, Channel Flow

Module 9e.

Runoff Estimation Methods

Runoff Estimation Methods



NRCS TR55

(other SCS methodologies)

Rational Method

Modified Rational Method

Others

Runoff estimates

- Estimate pre-development runoff flows, volume, hydrograph
    - Determine allowable release rates
- Estimate post-development runoff flows, volume, hydrograph

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Rational Method

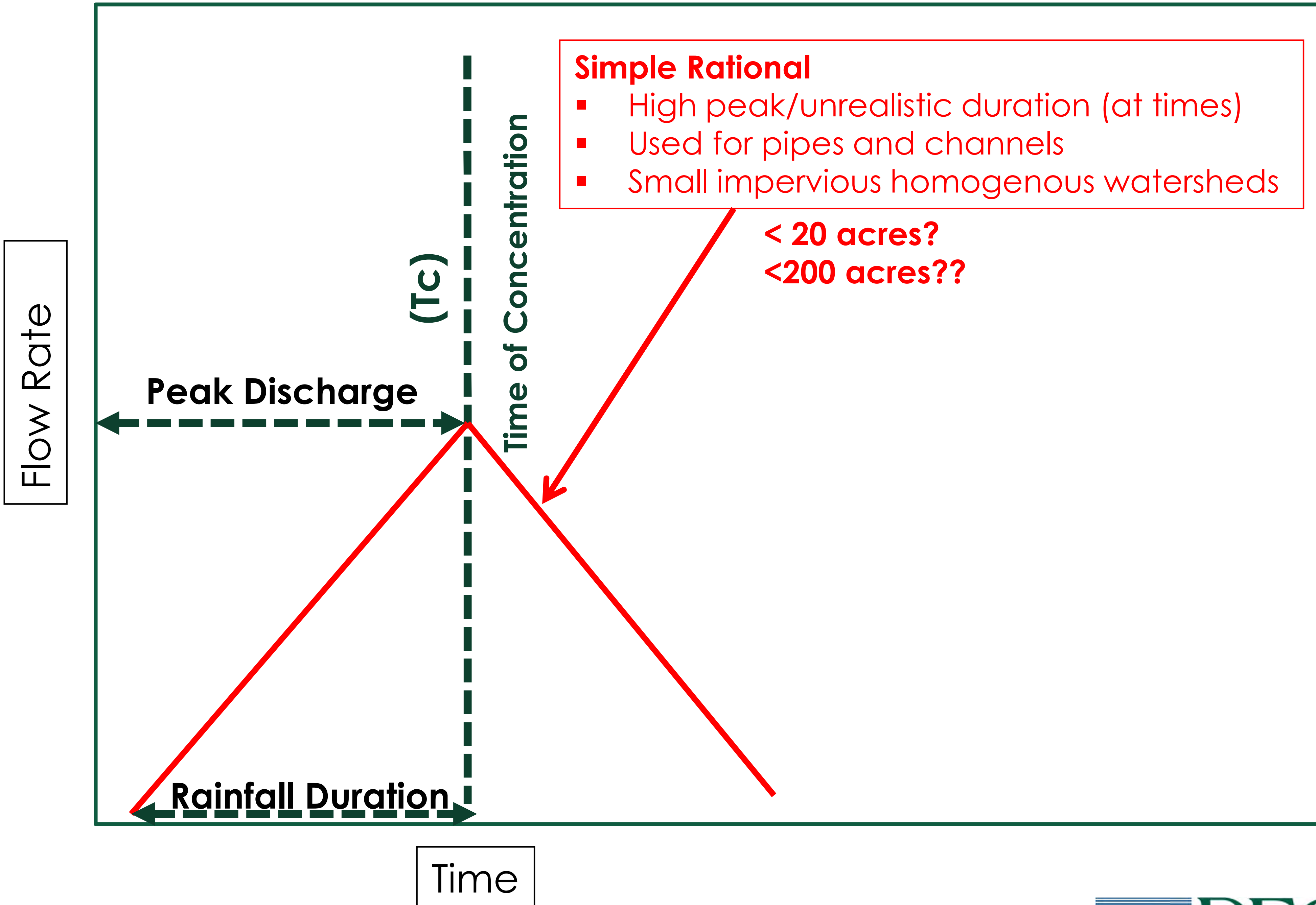
- Estimates peak rate of runoff

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

INFLOW HYDROGRAPHS



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Time of Concentration

- Most consistent source of error for rational method
- Typically overland flow and channel flow
- Minimum of 5 minutes
- Used to determine rainfall intensity (I)
- Critical for accuracy of rational method

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Rainfall Intensity

Rational Formula

$$Q = C \times \boxed{I} \times A$$

Assume time of concentration equals storm duration to find intensity

I = design rainfall intensity, in inches per hour, for a duration equal to the time of concentration of the watershed

Rainfall Intensity

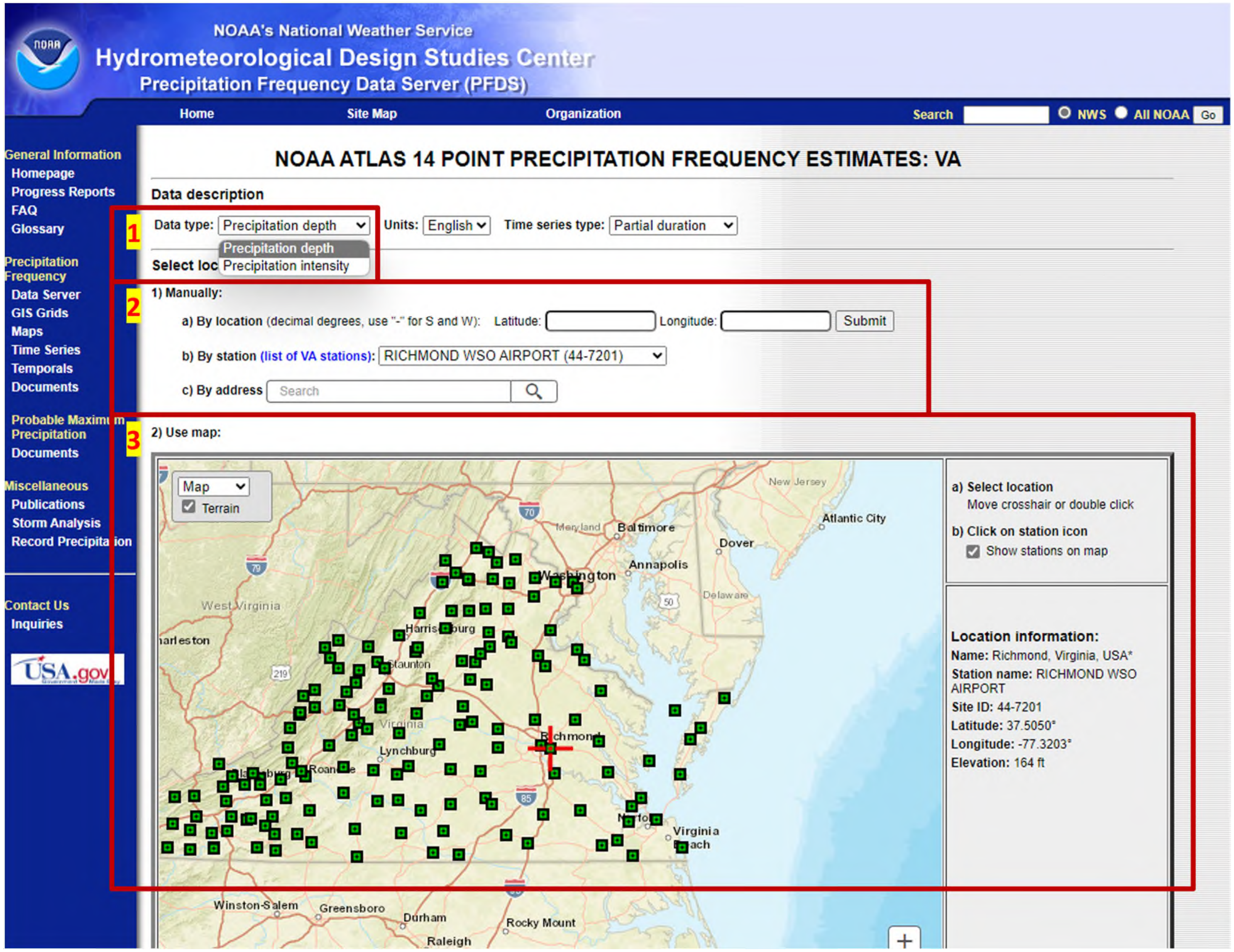
Rational Formula

$$Q = C \times \boxed{I} \times A$$

- For given return period (1-, 2-, 10-year storm)
- Select proper Intensity-Duration-Frequency (IDF) curve or proper value from NOAA Atlas 14 Table

I = design rainfall intensity, in inches per hour, for a duration equal to the time of concentration of the watershed

Rainfall Intensity



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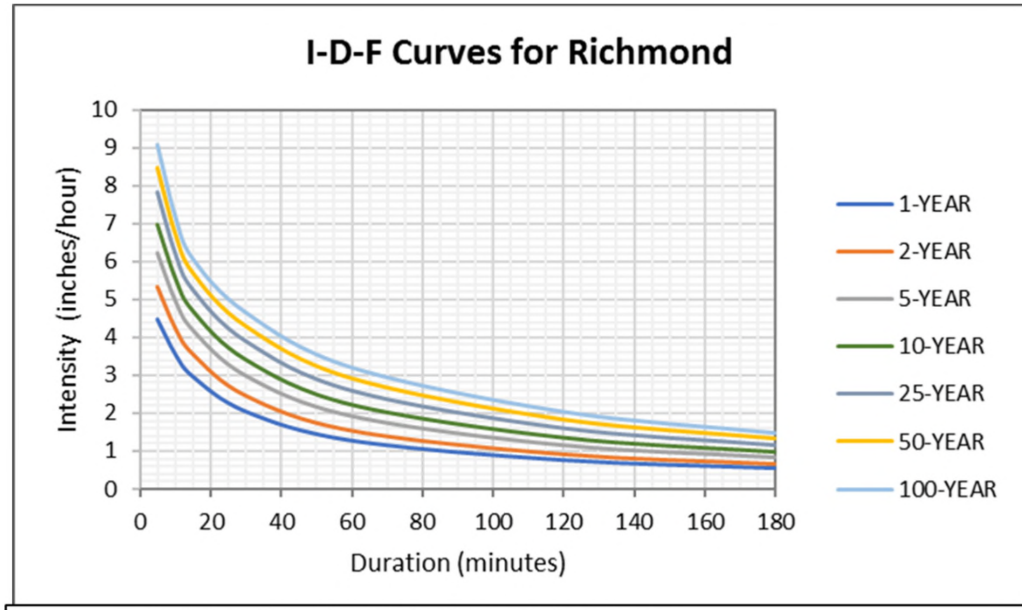
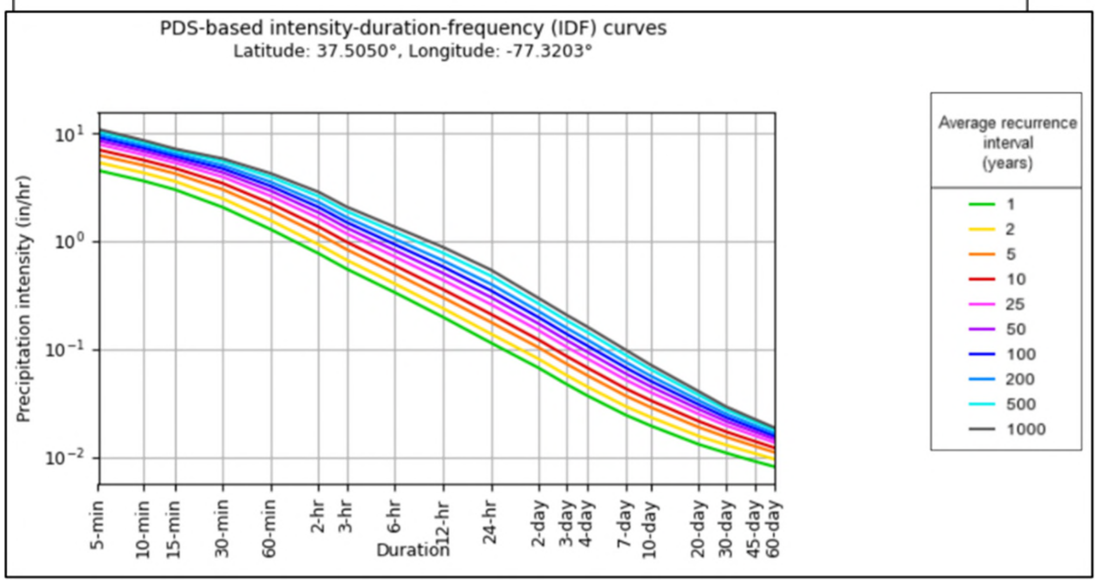
Rainfall Intensity





Older Format IDF curves from NOAA Atlas 14

New Format IDF Curves From NOAA Atlas 14

Rainfall Intensity

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/hour)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
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)
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** (0.077-0.095)	**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

Exercise:

Richmond

Tc = 5 minutes

1-year storm frequency

i= 4.51

VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Rational Method

Chapter 6 - Hydrology

Appendix 6C-1 B, D, and E Factors - Application

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)

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

Exercise:
Richmond
Tc = 5 minutes
1-year storm frequency

i=46.27/(5=11.01)$^{.84}$
i= 4.50 in/hr.

Runoff Coefficient (C)

Rational Formula

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

C = dimensionless runoff coefficient, dependent upon land use

Runoff Coefficient (C)

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

Estimates peak rate of runoff from drainage area

- Fraction between 0 to 1
- Represents relationship between rainfall and runoff
- Based on urban land use
- Proportional to % impervious cover
- Coefficients found in many publications including VDOT Drainage Manual (examples on page 56-57 of PG)

Rational Method

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

Estimates peak rate of runoff from drainage area

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**			**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			

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

Runoff Coefficient (C)

- Drainage area with multiple land uses with different C values, weighted C value can be calculated

Example:

10.0 acre drainage area with 2 different land uses

- ❑ 2 acres of parking lot (C = 0.95) and
- ❑ 8 acres of park (C = 0.25)

Runoff Coefficient (C)

- Calculate (C x A) value for each land use:

  C_{lot} **x** A_{lot} **= 0.95 x 2 = 1.9**

  C_{park} **x** A_{park} **= 0.25 x 8 = 2.0**

- Add (C x A) values together and divide sum by total area:

  (1.9 + 2.0)/10 = 3.9/10 = 0.39 = weighted C

Adjustment for Infrequent Storms

With adjustment, Rational Formula expressed as follows:

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

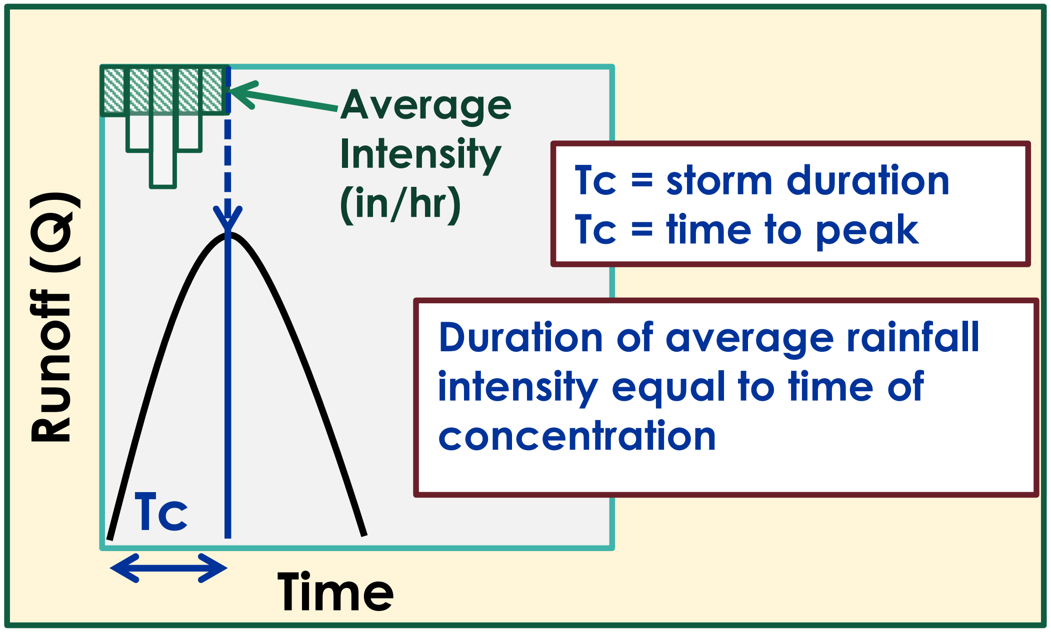
C_f values are provided in Table 9-6

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



Frequency of rainfall and runoff events similar

Rainfall

1. Uniform intensity and max discharge when entire watershed contributing

2. Storm duration equals *Tc* equals time to reach peak discharge

Rational Method - Limitations

- Assumptions limit drainage area to 200 acres (hydrograph method/computer simulation)
- Presence of bridges, culverts, storm sewers may restrict flow
- Storage routing recommended for flow beyond restrictions

Rational Method - Limitations

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

Variation for sizing detention facilities

Iterative - Determine rainfall duration that produces **maximum storage volume**

Analyze different durations to find greatest storage volume

(**critical storm duration**)

Modified Rational Method

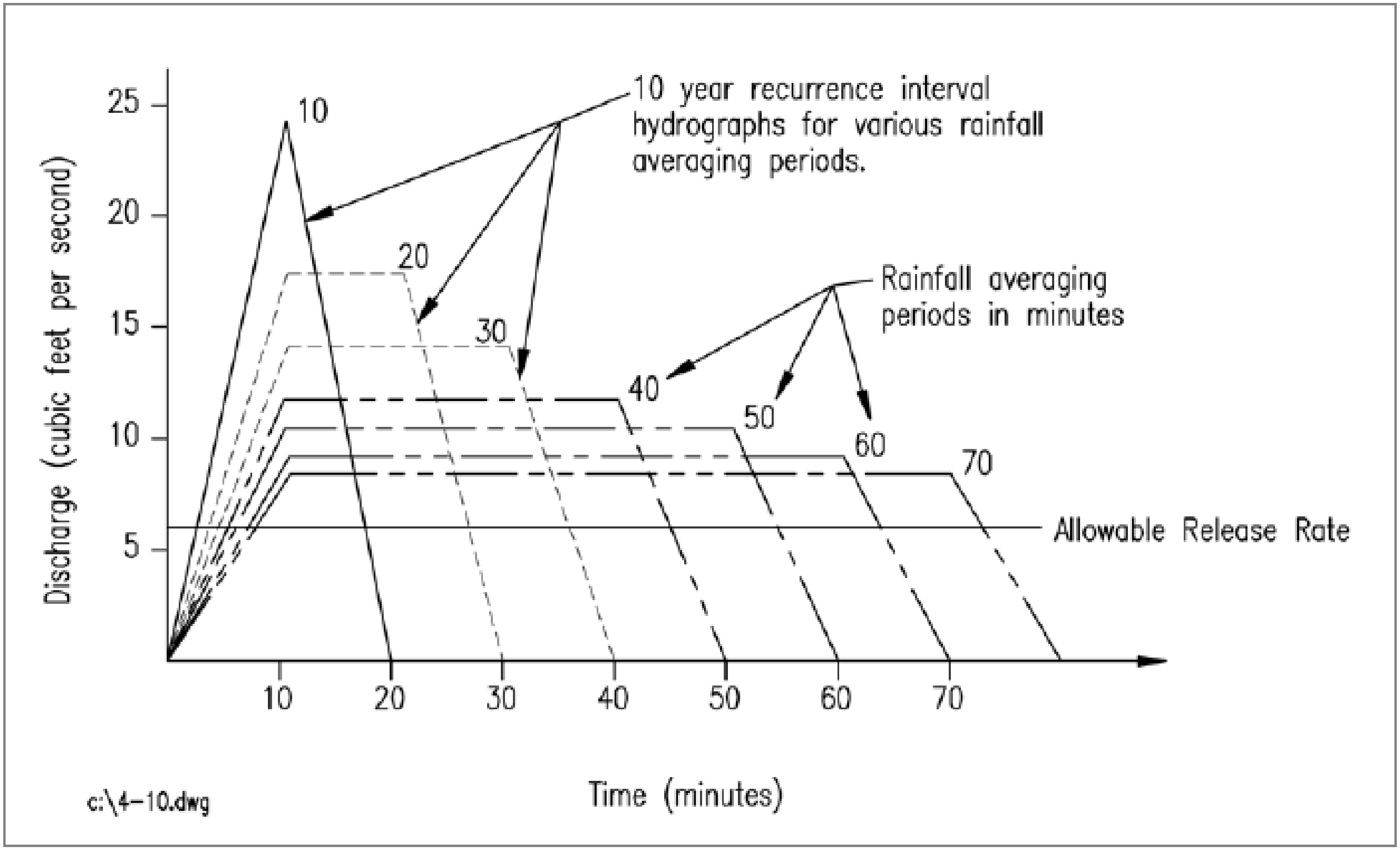


Figure 9-32. Modified Rational Method Runoff Hydrographs (VSWHB)

Modified Rational Method 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

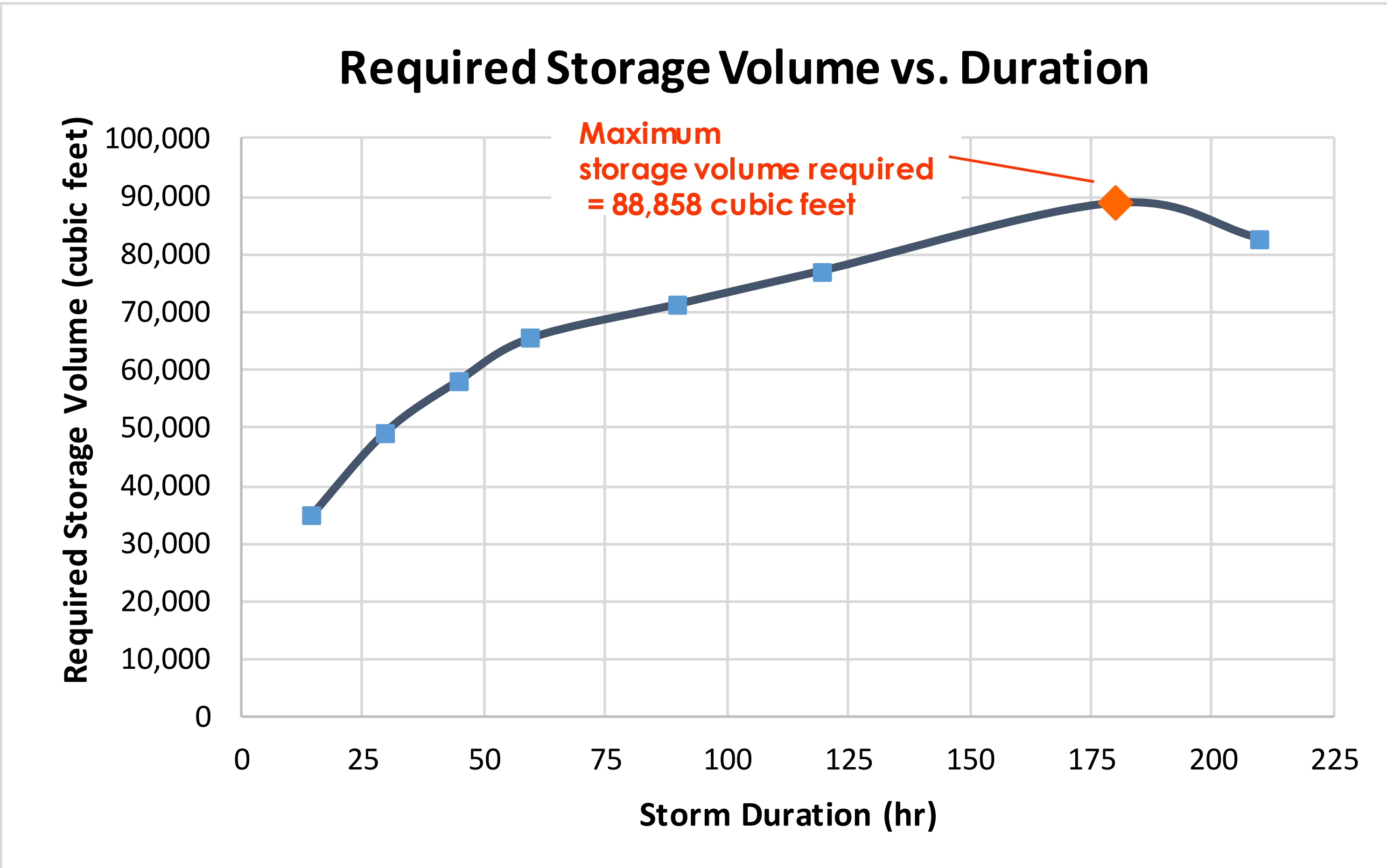
▲ Peak flow = Q = CIA Example: 0.7 x 4.8 in/hr x 11.88 acres = 39.9 cfs

■ 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

Modified Rational Method Example



Modified Rational Method

- An alternative solution: the Modified Rational Method-Critical Storm Duration
- A direct solution can be calculated through equations.
- Additional information available for this method is in Chapter 11 of the VDOT Drainage Manual.

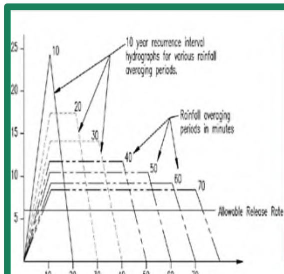
Q&A

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

Runoff Coefficients

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

Rational Method



Modified Rational Method