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Module 3

Stormwater Engineering Concepts

Virginia Department of Environmental Quality

Module 3 Content

- 3a. Introduction
- 3b. Urban hydrology for small watersheds (TR-55)
  - Estimating runoff
  - Time of concentration and travel time
  - Peak discharge
  - Storage volume for detention basins
  - Synthetic rainfall distributions and rainfall data sources
- 3c. Rational Method and Modified Rational Method
- 3d. Hydraulic Control Design

3a. Introduction

- **Part II B**
  - Design storms: 1-, 2- and 10-year 24-hour
  - Rainfall frequency data: NOAA Atlas 14
  - NRCS synthetic 24-hour rainfall distribution and models
    - TR-55 and TR-20
    - Army Corps hydrologic and hydraulic methods or other standard methods
  - Drainage areas $\leq$ 200 acres: Rational or Modified Rational Method

3a. Introduction

- **Part II C**
  - Impacts measured at **each point of discharge** and **include runoff from balance of watershed**
  - Design storms: **24-hour** (NRCS rainfall distribution) or **storm of critical duration**
  - Subdivisions: Apply SWM criteria to **whole LDA**
  - Hydrologic parameters: Reflect **ultimate land disturbance**

3a. Introduction

- **Part II C (continued)**
  - Pervious lands:

    Assumed to be (prior to development):
    - in **good condition**
    - with **good cover** or
    - with **conservation treatment**

3b: Urban Hydrology for Small Watersheds (TR-55)

NRCS publication Technical Release Number 55 (TR-55): Urban Hydrology for Small Watersheds, 2nd edition (June 1986)

See Resources Section for link to TR-55 manual Review!

3b: Urban Hydrology for Small Watersheds (TR-55)

- TR-55 used for estimating **peak discharges** from urban watersheds
  1. Graphical method
  2. Tabular method

3b1. Estimating Runoff

- Curve Number (CN) determination

CN indicates runoff potential of an area

3b1. Estimating Runoff

- Information needed:
  - Hydrologic soil group
  - Hydrologic condition
    - Cover type
    - Treatment
  - Antecedent runoff condition
  - Connected vs. unconnected

3b1. Estimating Runoff

- Hydrologic Soil Groups

Group A: Low runoff potential

Group B: Moderately low runoff potential

Group C: Moderately high runoff potential

Group D: High runoff potential

3b1. Estimating Runoff

- Hydrologic conditions
  - Effects of **cover type and treatment** on infiltration and runoff




3b1. Estimating Runoff

- Hydrologic conditions (continued)
  - Treatment = Management of cultivated agricultural lands
  - Existing or undeveloped land considered to be in **good condition**
    - Results in lower existing peak runoff rates

Table 3-2 Runoff Curve Numbers for Urban Areas

Cover description: Cover type and hydrologic condition	Average percent impervious area [2]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

Table 3-3 Runoff Curve Numbers for Other Agricultural Lands

Cover description: Cover type	Hydrologic condition	Hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. 2/	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. 3/	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 4/	48	65	73
Woods—grass combination (orchard or tree farm). 5/	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. 6/	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 4/	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
[illegible]

3b1. Estimating Runoff

- Antecedent runoff condition
  - Index of runoff potential before a storm event

3b1. Estimating Runoff

- Connected vs. unconnected
  - Consider:
    - % **impervious area** *and*
    - **conveyance** to drainage system

3b1. Estimating Runoff

Connected impervious area:

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

Unconnected impervious area:

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

3b1. Estimating Runoff

- Connected vs. unconnected
  - CN values developed assuming:
    - Pervious urban areas ~ pasture (good)
    - Impervious areas directly connected have CN of 98

3b1. Estimating Runoff

- Connected vs. unconnected
  - **Total impervious area < 30%** **and** Impervious area **not directly connected**
    - *designer can use Figure 2-4 of TR-55 to determine CN (Fig. 3-4 in PG)*
  - **Total impervious area ≥ 30%**
    - *designer can use Figure 2-3 from TR-55 to adjust CN (Fig. 3-3 in PG)*

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Figure 3-3 Composite CN with Connected Impervious Area or IA ≥ 30% of Drainage area

Figure 2-3 Composite CN with connected impervious area.

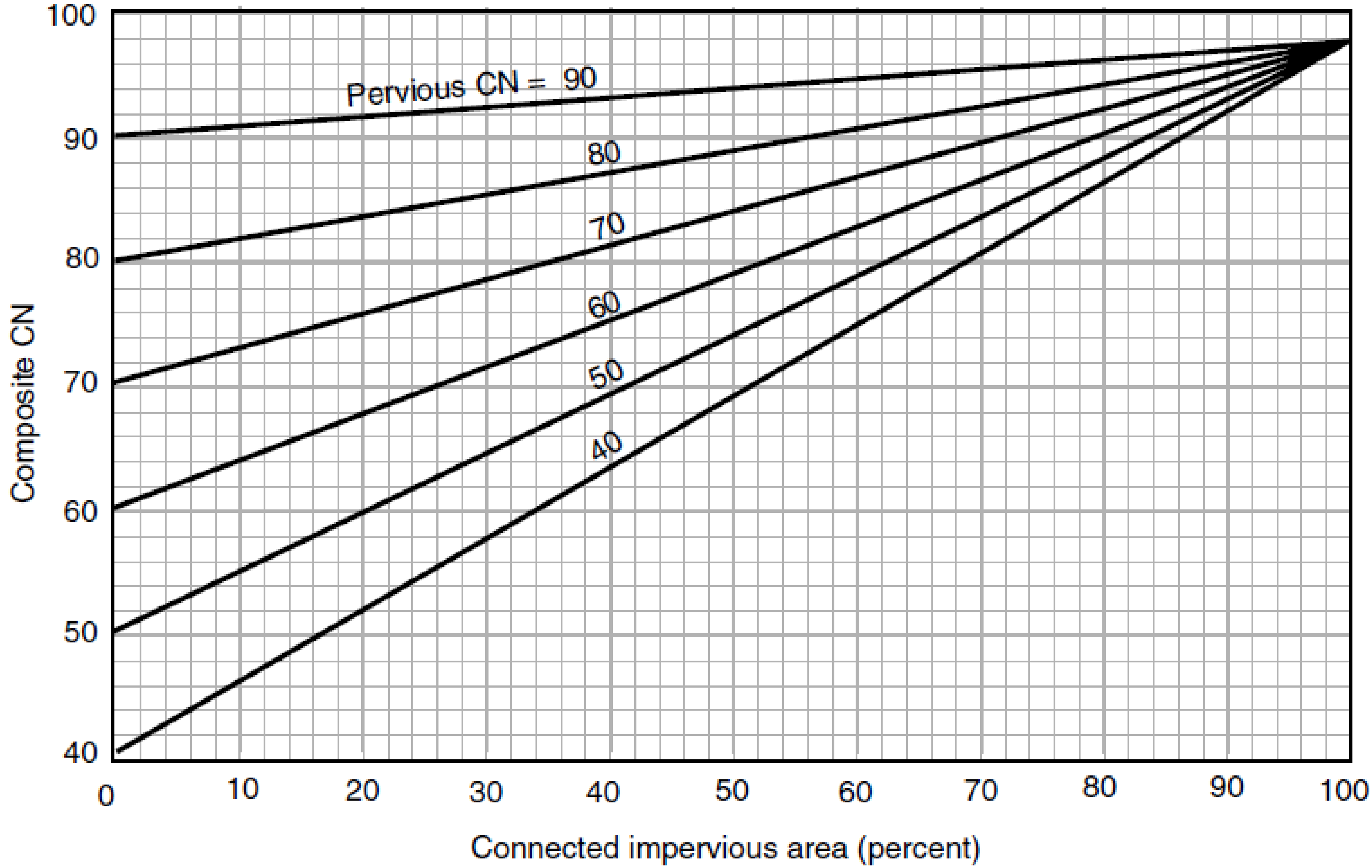
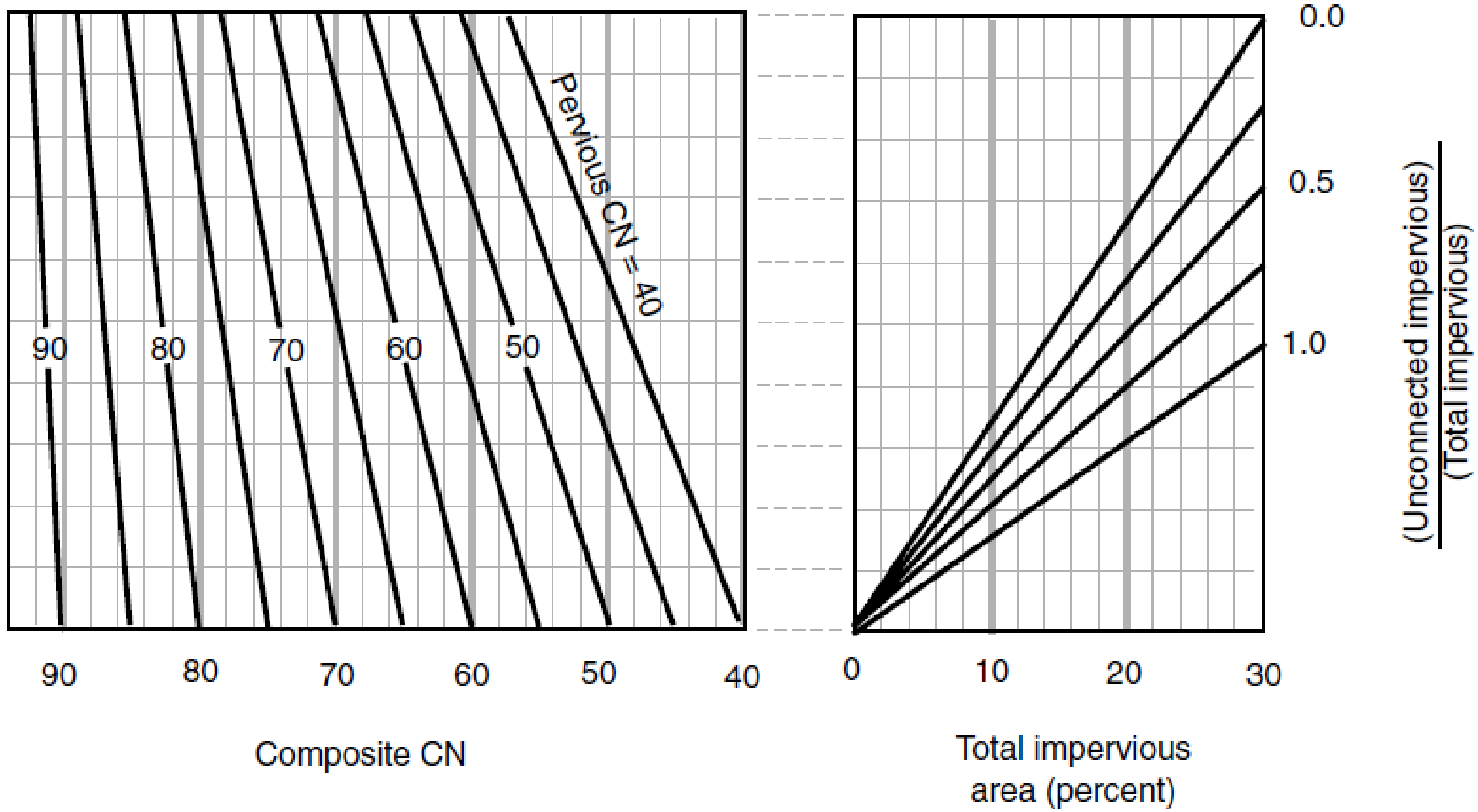


Figure 3-4 Composite CN with Unconnected Impervious Area and Total IA < 30%

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



3b1. Estimating Runoff

- Runoff equation
  - Used to express how much runoff volume generated by certain volume of rainfall
  - Attempts to quantify losses before runoff begins
  - Runoff computed is fraction of rainfall

3b1. Estimating Runoff

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

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

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

CN = Curve number
I_a *= Initial abstraction (in) = 0.2 x S*

Table 3-5 I_a Values for Runoff Curve Numbers

Table 5-1 I_a values for runoff curve numbers

Curve number	I_a (in)	Curve number	I_a (in)
40	3.000	70	0.857
41	2.878	71	0.817
42	2.762	72	0.778
43	2.651	73	0.740
44	2.545	74	0.703
45	2.444	75	0.667
46	2.348	76	0.632
47	2.255	77	0.597
48	2.167	78	0.564
49	2.082	79	0.532
50	2.000	80	0.500
51	1.922	81	0.469
52	1.846	82	0.439
53	1.774	83	0.410
54	1.704	84	0.381
55	1.636	85	0.353
56	1.571	86	0.326
57	1.509	87	0.299
58	1.448	88	0.273
59	1.390	89	0.247

Runoff Equation Example 3-1

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

P = rainfall (in)
CN = runoff curve number
S = potential maximum retention after runoff begins (in)

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Runoff Equation Example 3-1

P = rainfall (in)

CN = runoff curve number

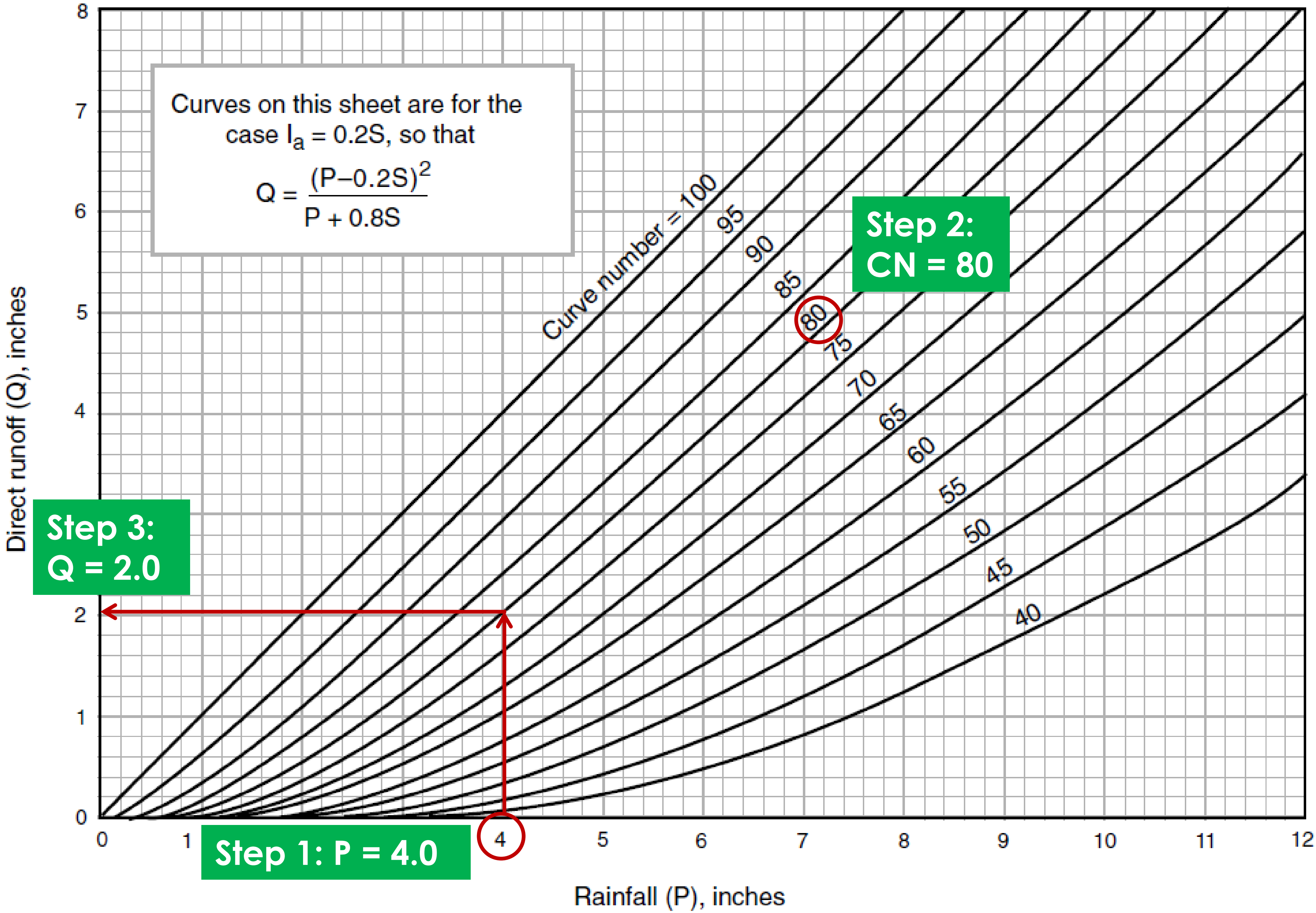
S = potential maximum retention after runoff begins (in)

$$S = \left(\frac{1000}{CN}\right) - 10 = \left(\frac{1000}{80}\right) - 10 = 2.5$$

I_a= initial abstraction (in) = **0.2 x S = 0.2 x 2.5 = 0.5**

$$Q = \frac{(P - 1_a)^2}{(P - 1_a) + S} = \frac{(4.0 - 0.5)^2}{(4.0 - 0.5) + 2.5} = 2.04$$

Runoff Equation Example 3-1



Runoff Equation Example 3-1

PG 20

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

Step 1:
P = 4.0

Step 2:
CN = 80

Step 3:
Q = 2.04

3b2: Time of Concentration, Travel Time

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

Sum of time increments for each flow segment

T_c = Σ (overland flow + shallow concentrated flow + channel flow)

3b2: 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

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

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3b3: Peak Discharge

TR-55 presents two methods for estimating peak discharge:

- **Graphical Method**
  - Provides **peak discharge** and **runoff volume**
- **Tabular Method**
  - Provides **peak discharge**, **runoff volume**, and a **runoff hydrograph**

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3b4: Storage Volume for Detention Basins

- Ways to control peak discharges
- Simplified procedure for estimating required storage volume (V_s)
- Suitable for estimating required storage for **preliminary design**
- **Not** suitable for final design

3b4: Storage Volume for Detention Basins

- Information needed to estimate storage volume (V_s) :
  - Peak outflow discharge (q_o)
  - Peak inflow discharge (q_i)
  - Runoff volume (V_r)

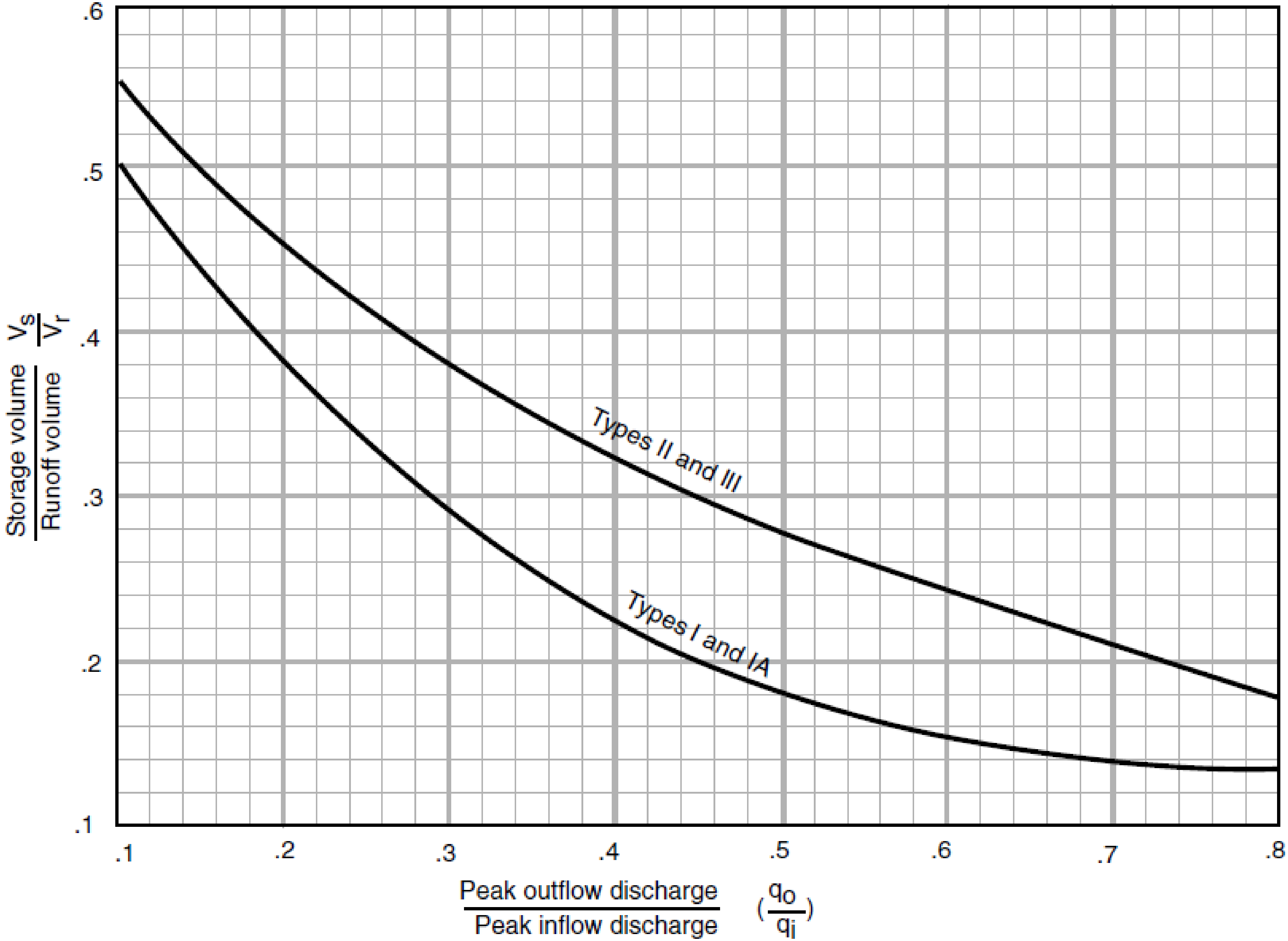
3b4: Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required
  1. Determine q_o
  2. Estimate q_i (chapters 4 or 5 of TR-55)

3b4: Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)
  3. Compute q_o/q_i and determine value for V_s/V_r from Figure 3-9 (pg 37)

Figure 3-9 Approximate Detention Basin Routing



3b4: Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)

4. Q (in inches) was determined when computing q_i in step 2
   - Now convert to units in which V_s is to be expressed

3b4: Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)

5. Use results of steps 3 and 4 to compute V_s

$$V_s = V_r x \left(\frac{Vs}{Vr} \right)$$

Vr = runoff volume (acre-ft)

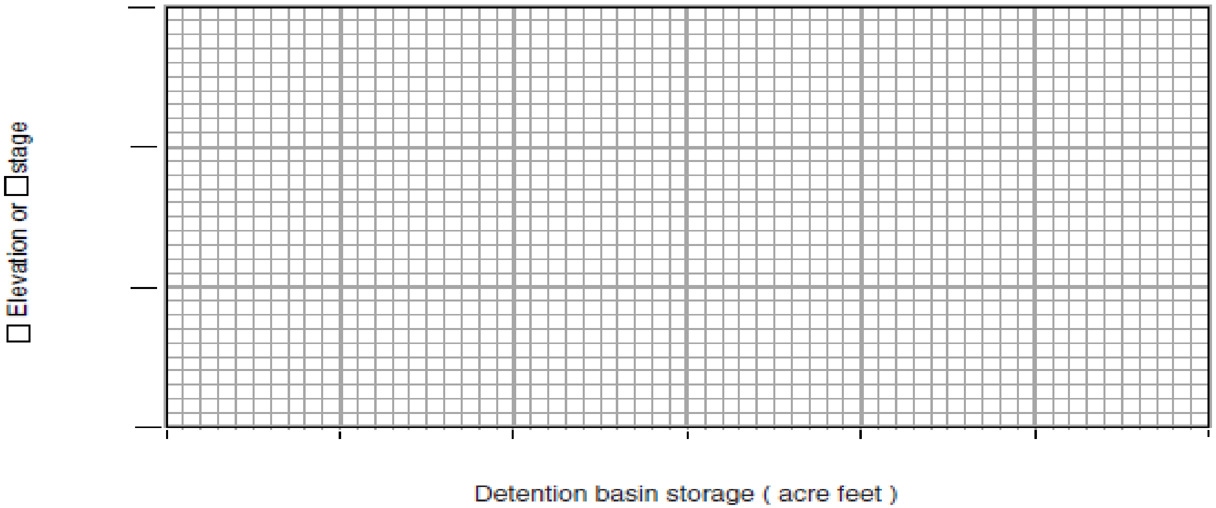
Vs = storage volume required (acre-ft)

(Vs/Vr) from figure 3-9

Worksheet 6a: Detention basin storage, peak outflow discharge (q_o) known

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed



1. Data:
   Drainage area .... A_m = __________ mi²
   Rainfall distribution type (I, IA, II, III) = __________

	1st Stage	2nd Stage
2. Frequency .... yr		
3. Peak inflow discharge q_i .... ft³/s (from worksheet 4 or 5b)		
4. Peak outflow discharge q_u .... ft³/s		1/
5. Compute $\frac{q_o}{q_i}$		

6. $\frac{V_s}{V_r}$ .... (Use $\frac{q_o}{q_i}$ with figure 6-1)		
7. Runoff, Q .... in (From worksheet 2)		
8. Runoff volume V_r.................. ac ft ($V_r = QA_m$ 53.33)		
9. Storage volume, V_s .... ac-ft ($V_s = V_r$ ($\frac{V_s}{V_r}$))		
10. Maximum storage E_{max} (from plot)		

1/ 2nd stage q_o includes 1st stage q_o.

Worksheet 6a from TR-55 is useful for documenting inputs and results

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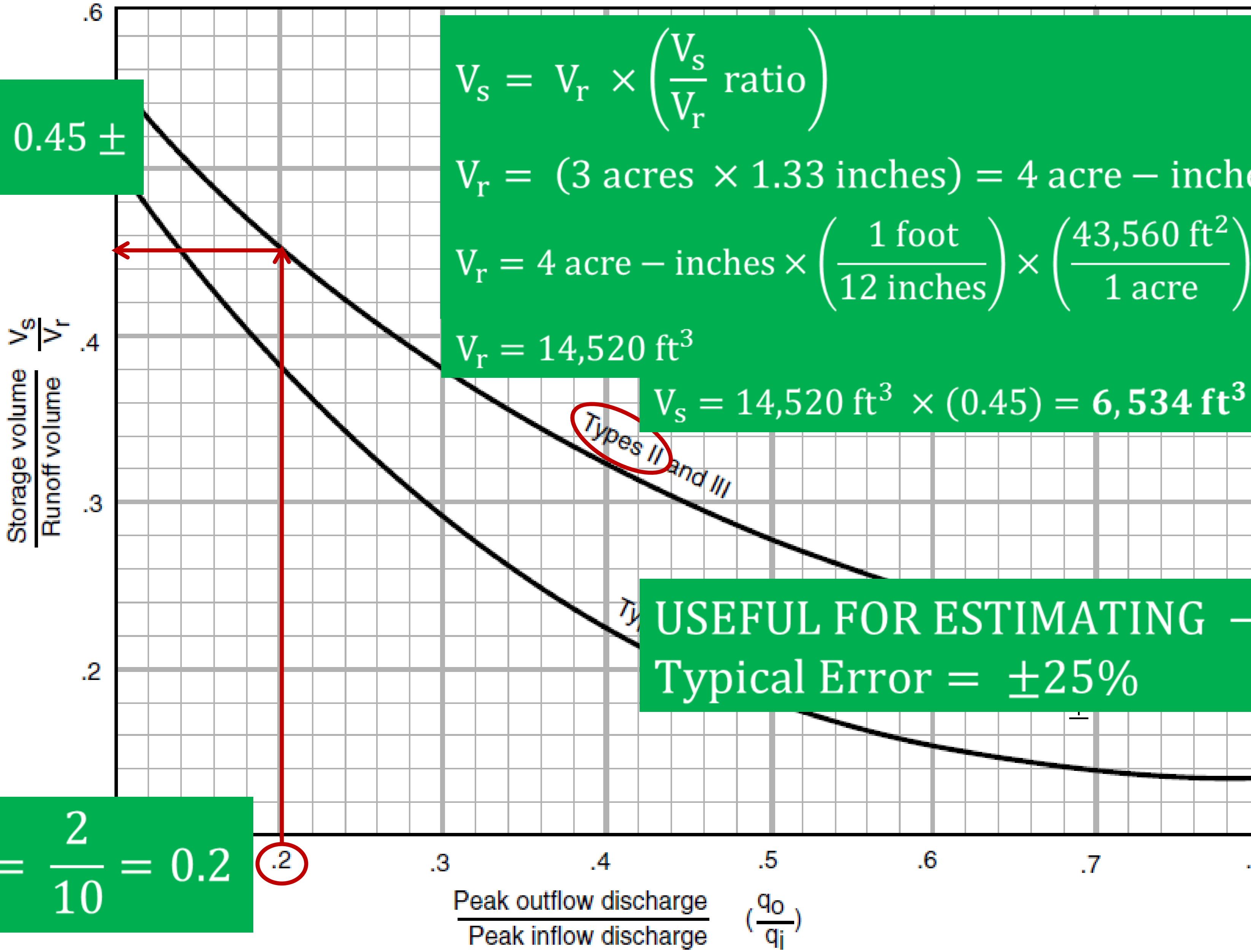
Example: Estimate Storage Volume

Given:

- 3-acre site in Richmond, Virginia (Type II)
- Developed discharge rate into the basin = 10 cfs = q_i
- Allowable discharge rate = 2 cfs = q_o
- Developed runoff volume = 1.33 inches

Example: Estimate Storage Volume



$$\frac{V_s}{V_r} = 0.45 \pm$$

$$V_s = V_r \times \left(\frac{V_s}{V_r} \text{ ratio}\right)$$

$$V_r = (3 \text{ acres } \times 1.33 \text{ inches}) = 4 \text{ acre} - \text{inches}$$

$$V_r = 4 \text{ acre} - \text{inches} \times \left(\frac{1 \text{ foot}}{12 \text{ inches}}\right) \times \left(\frac{43{,}560 \text{ ft}^2}{1 \text{ acre}}\right)$$

$$V_r = 14{,}520 \text{ ft}^3$$

$$V_s = 14{,}520 \text{ ft}^3 \times (0.45) = \mathbf{6{,}534 \text{ ft}^3}$$

USEFUL FOR ESTIMATING –
Typical Error = $\pm 25\%$

$$\frac{q_o}{q_i} = \frac{2}{10} = 0.2$$

3c: Rational Method

- The Rational Formula estimates the peak rate of runoff at any location in a drainage area

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

where:

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

3c: Rational Method

- **Runoff Coefficient, C**
  - Fraction of runoff associated with specific land cover
  - Recommended coefficients (Table 3-7, p.46)
- **Rainfall Intensity, I**
  - Average rate (in/hr) for storm duration equal to time of concentration
  - Given return period and T_c for drainage area, use **Intensity-Duration-Frequency** (I-D-F) curve

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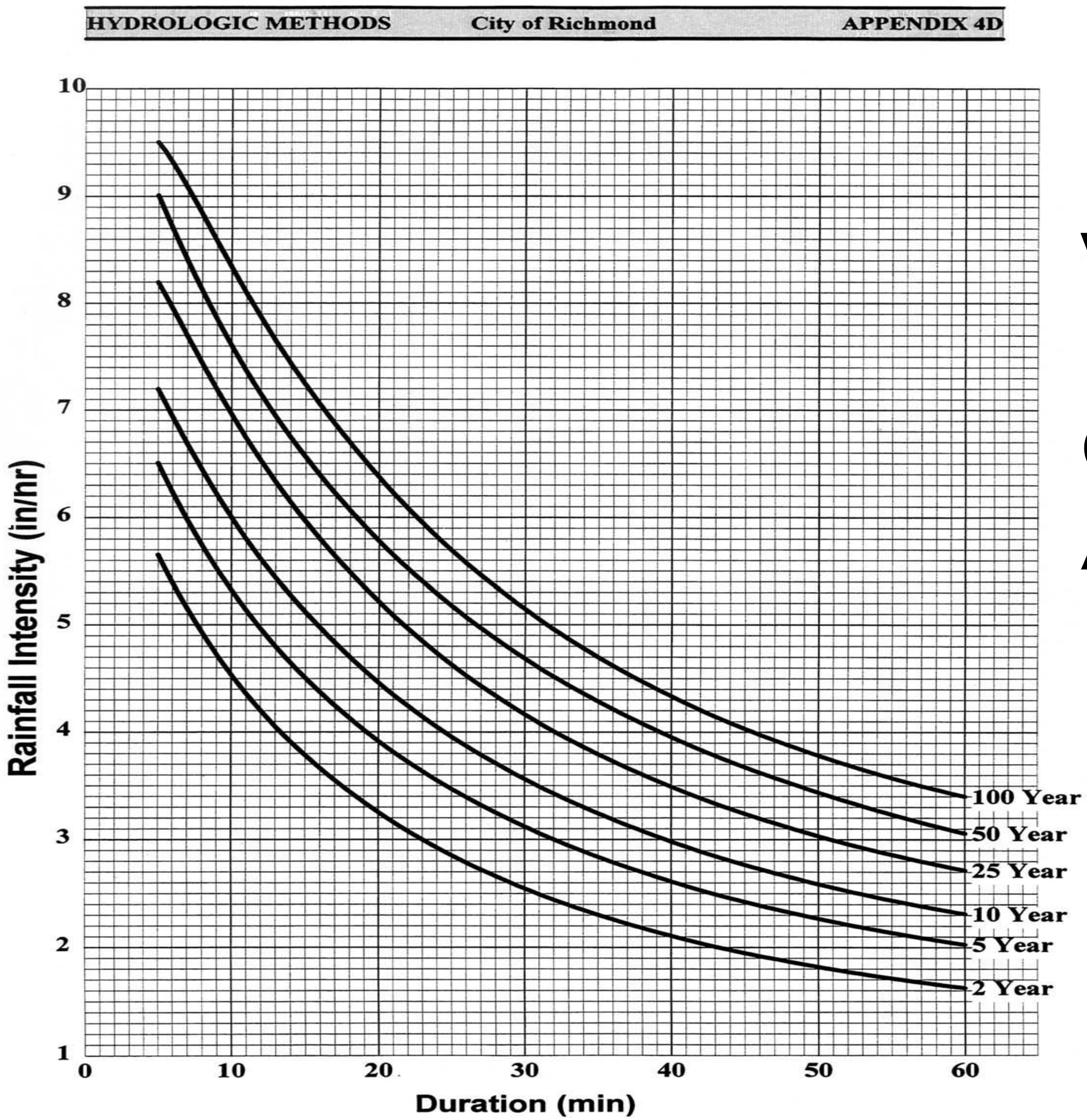
3c: Rational Method

Table 3-7 Rational Equation Runoff Coefficients
1999 SWM Handbook (page 4-20)

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

I-D-F Curve for Richmond



VSWMH - 1999 edition, Chapter 4, Appendix 4D

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3c: Modified Rational Method

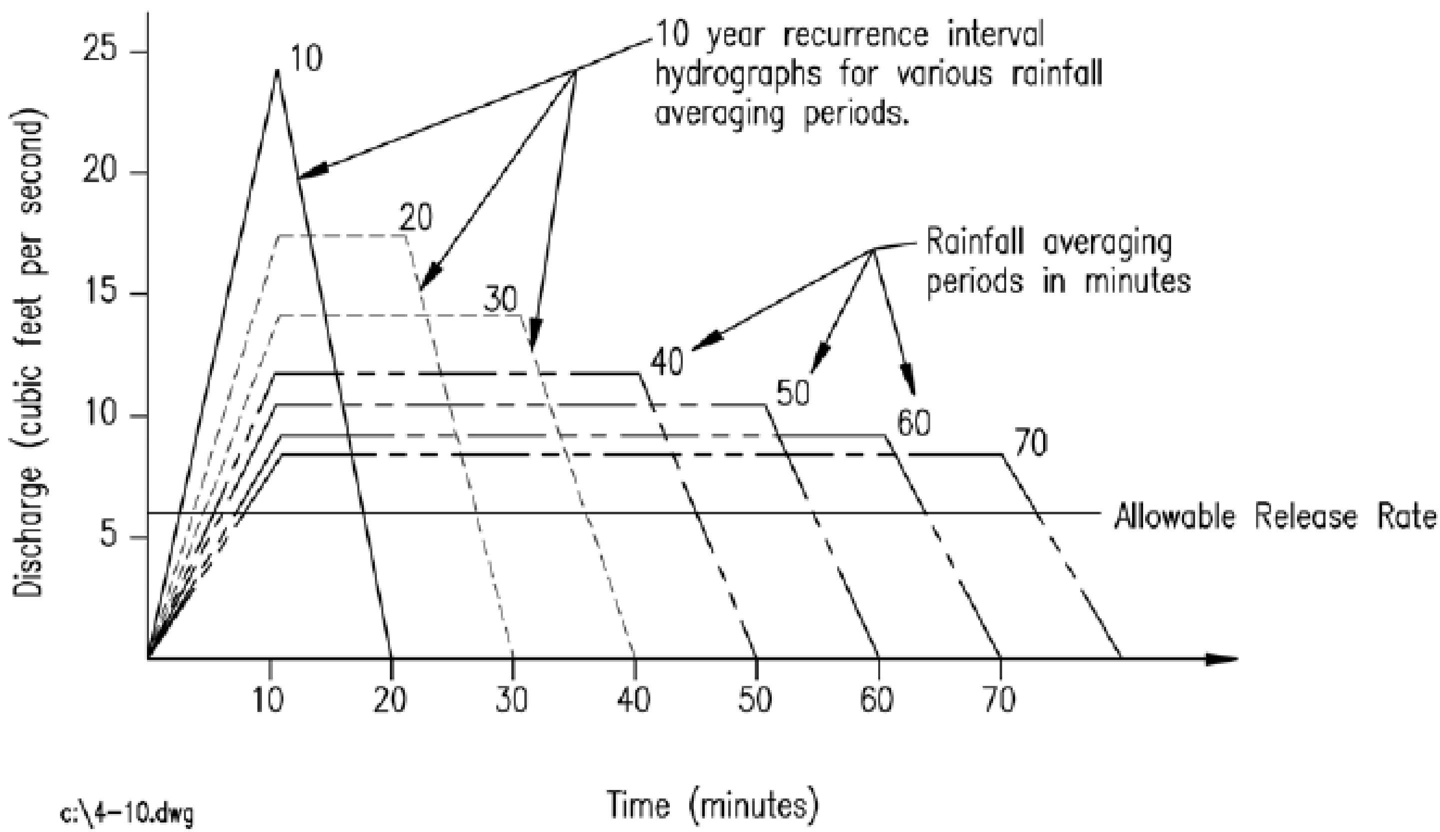
Variation of the rational method for sizing detention facilities

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

Analyze different durations to determine which requires greatest storage volume (**critical storm duration**)

3c: Modified Rational Method

Figure 3-13: Modified Rational Method Runoff Hydrographs
1999 SWM Handbook (page 4-27)



Design of hydraulic control structures

- Stormwater management facilities
- BMPs

Discharge rating cures

- Describe outflow discharge associated with elevation of upstream water

Hydraulic structures difficult to model: 1999 VSMHB Ch.5

3d: Hydraulic Control Design

A **weir** is a structure placed across a waterway or waterbody for regulating or measuring flow or discharge

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

where:

Q_w = weir discharge, cfs

C_w = dimensionless weir coefficient

L = length of weir, ft

h = hydraulic head, ft

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3d: Hydraulic Control Design

Table 3-9: Dimensionless Weir Coefficients 1999 SWM Handbook

WEIR FLOW COEFFICIENTS, C

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

3d: Hydraulic Control Design

An **orifice** is another type of structure used to control or measure discharge

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

where:

Q = orifice discharge, cfs

C = dimensionless orifice coefficient*

a = orifice area, ft2

g = gravitational acceleration, 32.2 ft/sec^2

h = hydraulic head, ft

VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Questions?