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PARTNERS FOR WHAT'S POSSIBLE

STORMWATER CONCEPTS

Rational Method, Pipe Sizing, and Conveyance

Pennsylvania Surveyors Conference 2023

Topics Covered

- Rational formula for peak runoff flows
- Manning's equation for pipe sizing
- Manning's Equation for swale design for overland flow

Conveyance Workshop Outcomes

- Estimate peak flow rates using the Rational Equation
- Size a channel using Manning's Equation
- Use Manning's equation to analyze and size channels and pipes flowing partially full
- Use the hydraulic elements chart for circular pipes to determine flow area, depth and velocity design conditions

Review Basic Concepts

- Water flows down hill
- We look at the effects of stormwater and development at certain points of interest
- Evaluate the effects using different methodologies and software
- Try to develop a reliable answer using consistent and correct application of the appropriate method
- There is no one right answer, but there are wrong answers
- Concepts need to be understood. Application needs to be practiced.

REVIEW BASIC CONCEPTS

- Criteria to needed to analyze stormwater runoff
  - Precipitation (rainfall) Event
  - Area
  - Cover
  - Intensity
    - Response of the land
    - Time of Concentration

Review Basic Concepts

- Precipitation (rainfall) Event
  - What design storm(s)?
  - What region of the state or country are we in?
- Area
  - Determine point(s) of interest (POI)
    - Where are we interested in looking?
    - Determine in pre not post

Review Basic Concepts

- Cover
  - Identify the cover types in combination with the hydrologic soil type
  - Calculate the cover coefficient
- Intensity (Response)
  - Determine the time of concentration
  - What is the longest amount of time any one drop of water in the drainage area will take to get to the POI
  - Longest hydraulic length

RATIONAL FORMULA

Rational Formula

- The equation

$$\boxed{q = CiA}$$

- q = peak flow in ft^3/s
- C = runoff coefficient varying from 0 to 1
- i = rainfall intensity in in/hr
- A = watershed area in acres.

Oldest & most common method for peak flow calculation

ASSUMPTIONS/LIMITATIONS

- Uniform rainfall intensity over the watershed occurs.
- Uniform rainfall intensity for the entire duration of the storm also occurs.
- The duration of the rainfall intensity (storm) is equal to the watershed time of concentration.
- The return period of peak flow is equal to return period of rainfall intensity

Equation Units

- Units are not homogeneous, but the units still work out as follows:

$$q = CiA = \frac{\text{acre-in}}{\text{hr}}$$

$$\frac{\text{acre-in}}{\text{hr}} = \frac{\text{in}}{\text{hr}} \times \frac{\text{ft}}{12\,\text{in}} \times \frac{\text{hr}}{3600\,\text{sec}} \times \text{acres} \times \frac{43{,}560\,\text{ft}^2}{\text{acres}}$$

$$\frac{\text{acre-in}}{\text{hr}} = 1.008\,\frac{\text{ft}^3}{\text{sec}}$$

Essentially the same–close enough for hydrology!

Runoff Coefficients

Description	Coefficient*
Homogeneous areas	
Pavement	
Asphalt and concrete	0.70 – 0.95
Brick	0.70 – 0.85
Porous	0.05 – 0.10
Lawns, sandy soil	
Flat (2%)	0.05 – 0.10
Average (2 to 7%)	0.10 – 0.15
Steep (>7 %)	0.15 – 0.20
Lawns, heavy soil	
Flat (2%)	0.13 – 0.17
Average (2 to 7%)	0.18 – 0.22
Steep (>7 %)	0.25 – 0.35
Composite areas by land use	
Business	
Downtown	0.70 – 0.95
Neighborhood	0.50 – 0.70
Residential	
Single family	0.30 – 0.50
Multi-units detached	0.40 – 0.60
Multi-units attached	0.60 – 0.75
Suburban	0.25 – 0.40
Apartment	0.50 – 0.75
Industrial	
Light	0.50 – 0.80
Heavy	0.60 – 0.90
Parks, cemeteries	0.10 – 0.25
Playgrounds	0.20 – 0.35
Railroad yards	0.20 – 0.35
Unimproved	0.10 – 0.30

* Range of C values presented are typical for return periods of 2 – 10 years. Higher values are appropriate for larger design storms.

Runoff coefficients by Rawls

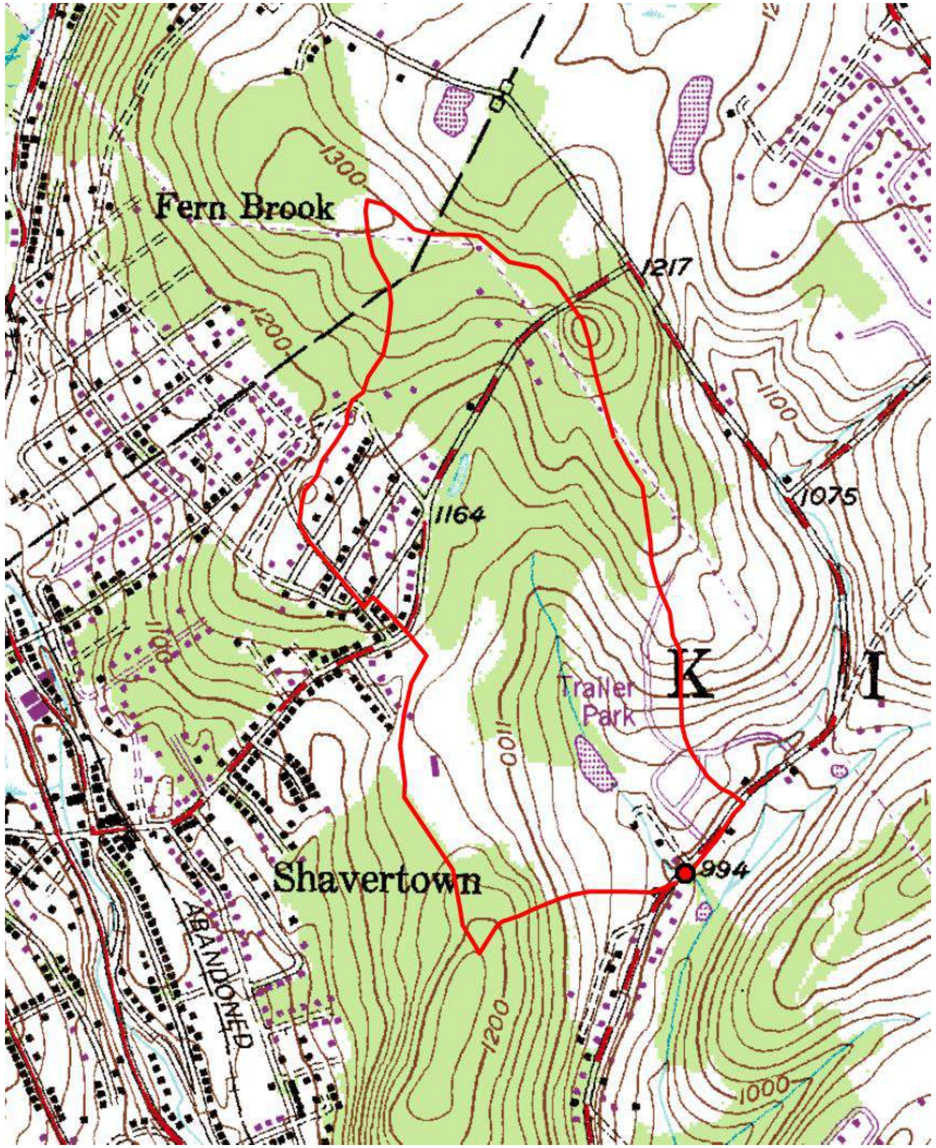
Land Use	*Hydrologic Soil Group and average surface slope*											
	A			*B*			*C*			*D*		
	0-2%	*2-6%*	*6%+*	*0-2%*	*2-6%*	*6%+*	*0-2%*	*2-6%*	*6%+*	*0-2%*	*2-6%*	*6%+*
Cultivated	0.08[a]	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
	0.14[b]	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Residential	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
1/8 acre lot	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Residential	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
1/4 acre lot	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Residential	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
1/3 acre lot	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Residential	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
1/2 acre lot	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.48
Residential	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
1 acre lot	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	0.69	0.69	0.69	0.69	0.70
	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.71	0.71	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	0.88	0.88	0.79	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets	0.70	0.71	0.72	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Open space	0.05	0.10	0.14	0.08	0.13	0.19	0.12	0.17	0.24	0.16	0.21	0.28
	0.11	0.16	0.20	0.14	0.19	0.26	0.18	0.23	0.32	0.22	0.27	0.39
Parking	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97

[a] Runoff coefficients for storm-recurrence intervals less than 25 years

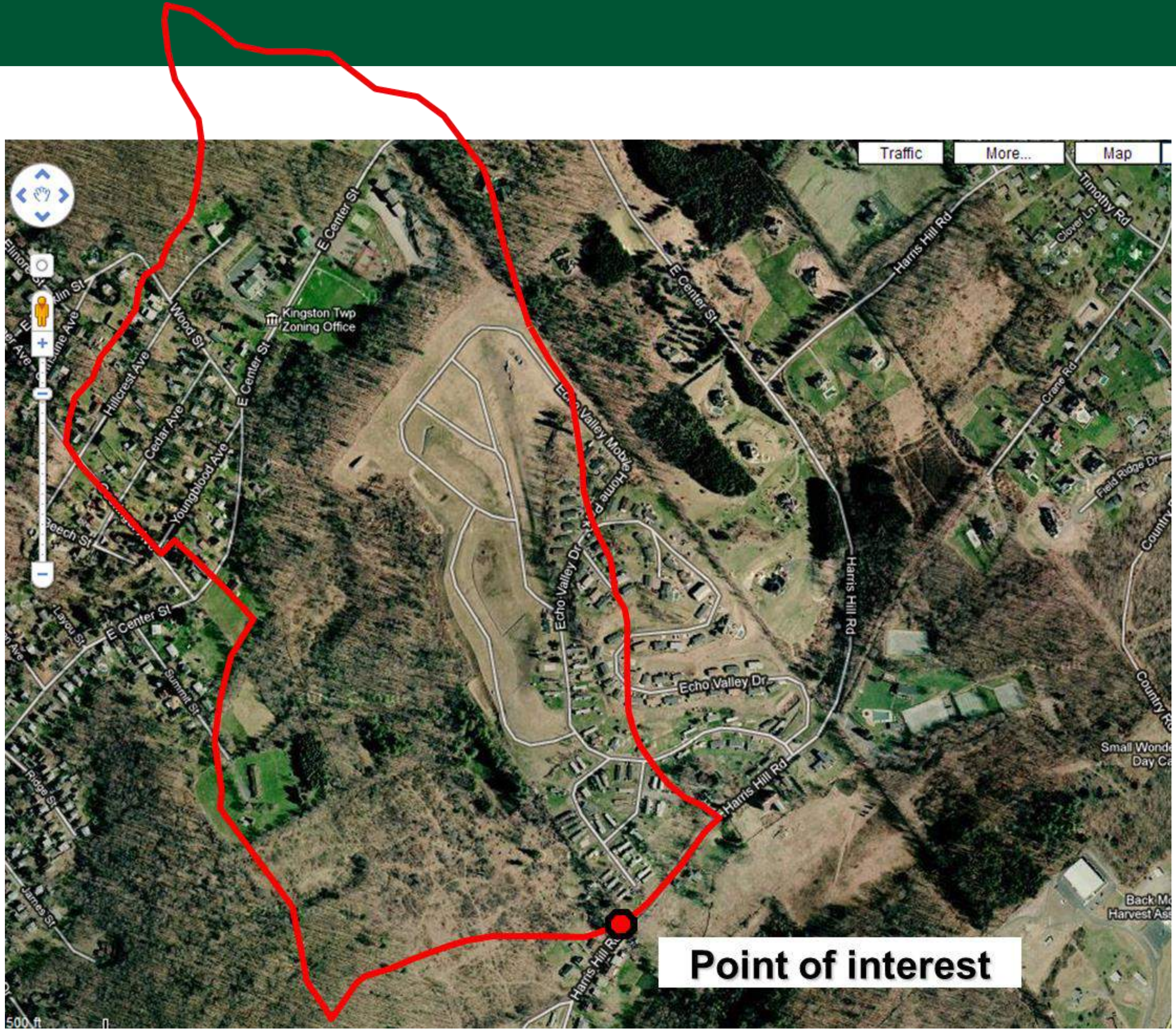
[b] Runoff coefficients for storm-recurrence intervals of 25 years or longer

ECHO VALLEY WATERSHED

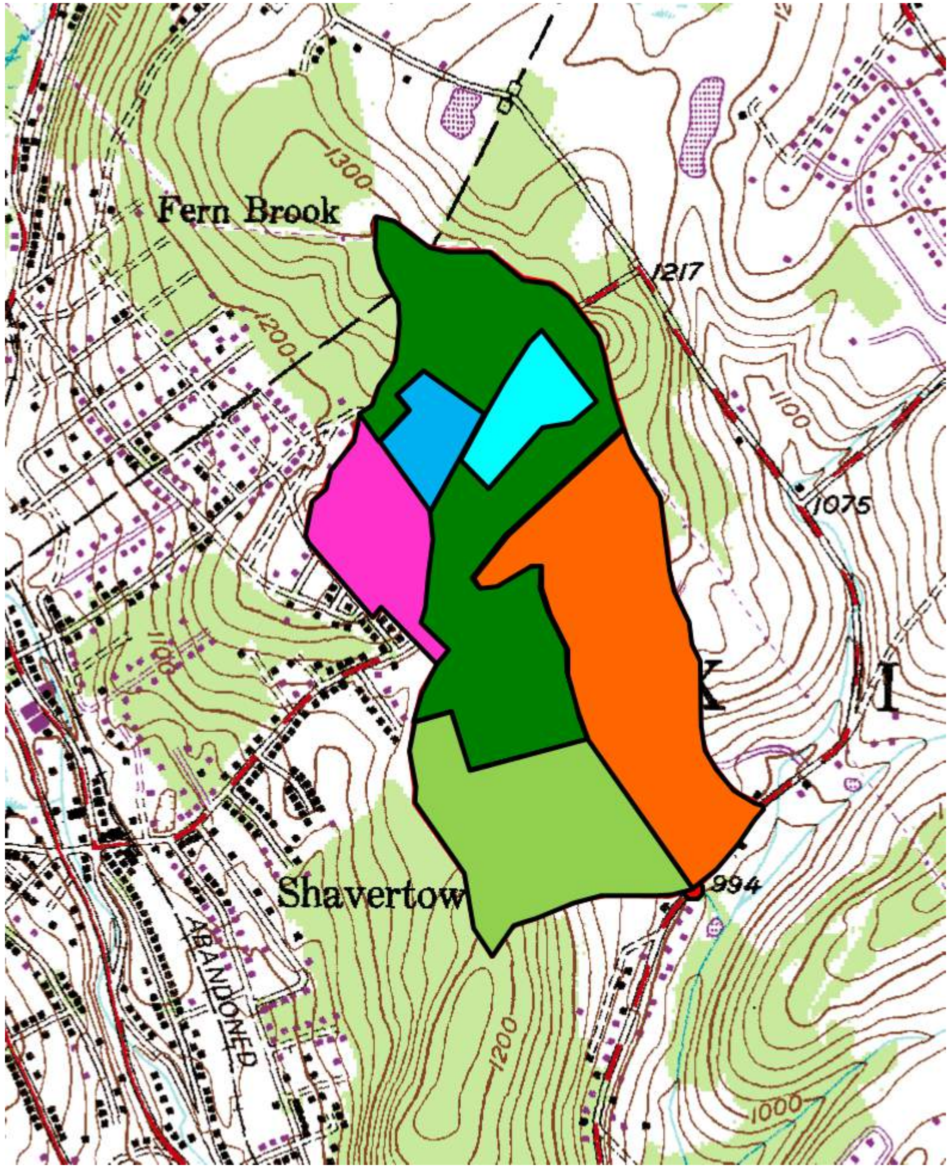
- Watershed from Part 1 workshop to illustrate the application of the Rational method



RUNOFF COEFFICIENTS - LAND USE/COVER FROM GOOGLE



Land use from Google and field survey



Land Use

Forest:	60.3 ac
Open space:	29.8 ac
Residential (1 A lots):	6.5 ac
Residential (1/3 A lots):	13.2 ac
Residential (1/4 A lots):	50.7 ac
Municipal Park:	8.5 ac
Total:	169.0 ac

RUNOFF COEFFICIENT WEIGHTING

- For watersheds with multiple land uses

$$C_w = \frac{\sum C_i A_i}{\sum A_i}$$

C_w	=	Weighted runoff coefficient
C_i	=	runoff coefficient of each individual land use
A_i	=	drainage area of each individual land use

WORKSHOP PRACTICE 1:

- Compute the weighted runoff coefficient C_w and 10-yr peak flow for the Echo Valley Watershed knowing that the soils are Type C, and slopes are 6+%.

Land use	*C*	*A*	*C x A*
Forest		60.3	
Open space		29.8	
Residential 1 acre		6.5	
Residential 1/3 acre		13.2	
Residential 1/4 acre		50.7	
Municipal Park		8.5	
		169.0	

$$C_{weighted} = \frac{\quad}{\quad} = \frac{\quad}{\quad}$$

Workshop Practice 1:

- C_w for Echo Valley Watershed
  - C soils, S = 6+%, 10 yr. event

Land use	*C*	*A*	*C x A*
Forest	0.16	60.3	
Open space	0.24	29.8	
Residential 1 acre	0.31	6.5	
Residential 1/3 acre	0.34	13.2	
Residential 1/4 acre	0.36	50.7	
Municipal Park	0.24	8.5	
		169.0	

$$C_{weighted} = \frac{\qquad}{\qquad} = \frac{\qquad}{\qquad}$$

WORKSHOP PRACTICE 1:

- C_w for Echo Valley Watershed
  - C soils, S = 6+%, 10 yr. event

Land use	*C*	*A*	*C x A*
Forest	0.16	60.3	9.65
Open space	0.24	29.8	7.15
Residential 1 acre	0.31	6.5	2.02
Residential 1/3 acre	0.34	13.2	4.49
Residential 1/4 acre	0.36	50.7	18.25
Municipal Park	0.24	8.5	2.04
		169.0	43.60

$$C_{weighted} = \frac{\quad}{\quad} = \frac{\quad}{\quad}$$

Workshop Practice 1:

- C_w for Echo Valley Watershed
  - C soils, S = 6+%, 10 yr. event

Land use	*C*	*A*	*C x A*
Forest	0.16	60.3	9.65
Open space	0.24	29.8	7.15
Residential 1 acre	0.31	6.5	2.02
Residential 1/3 acre	0.34	13.2	4.49
Residential 1/4 acre	0.36	50.7	18.25
Municipal Park	0.24	8.5	2.04
		169.0	43.60

$$\boxed{C = \frac{43.60}{169.0} = 0.26}$$

TIME OF CONCENTRATION - NRCS SEGMENTAL METHOD

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- Three flow types
  - Sheet – kinematic wave
  - Concentrated overland – "average velocity" method
  - Channel – Manning's equation

1. Sheet

$$T = \frac{0.42}{P_2^{0.5}}\left(\frac{nL}{S^{0.5}}\right)^{0.8}$$

2. Concentrated

$$T_{\text{pavement}} = \frac{L}{1220\,S^{0.5}}$$

$$T_{\text{grassed waterway}} = \frac{L}{968\,S^{0.5}}$$

$$T_{\text{short-grass pasture and lawn}} = \frac{L}{418S^{0.5}}$$

$$T_{\text{woodlands}} = \frac{L}{302\,S^{0.5}}$$

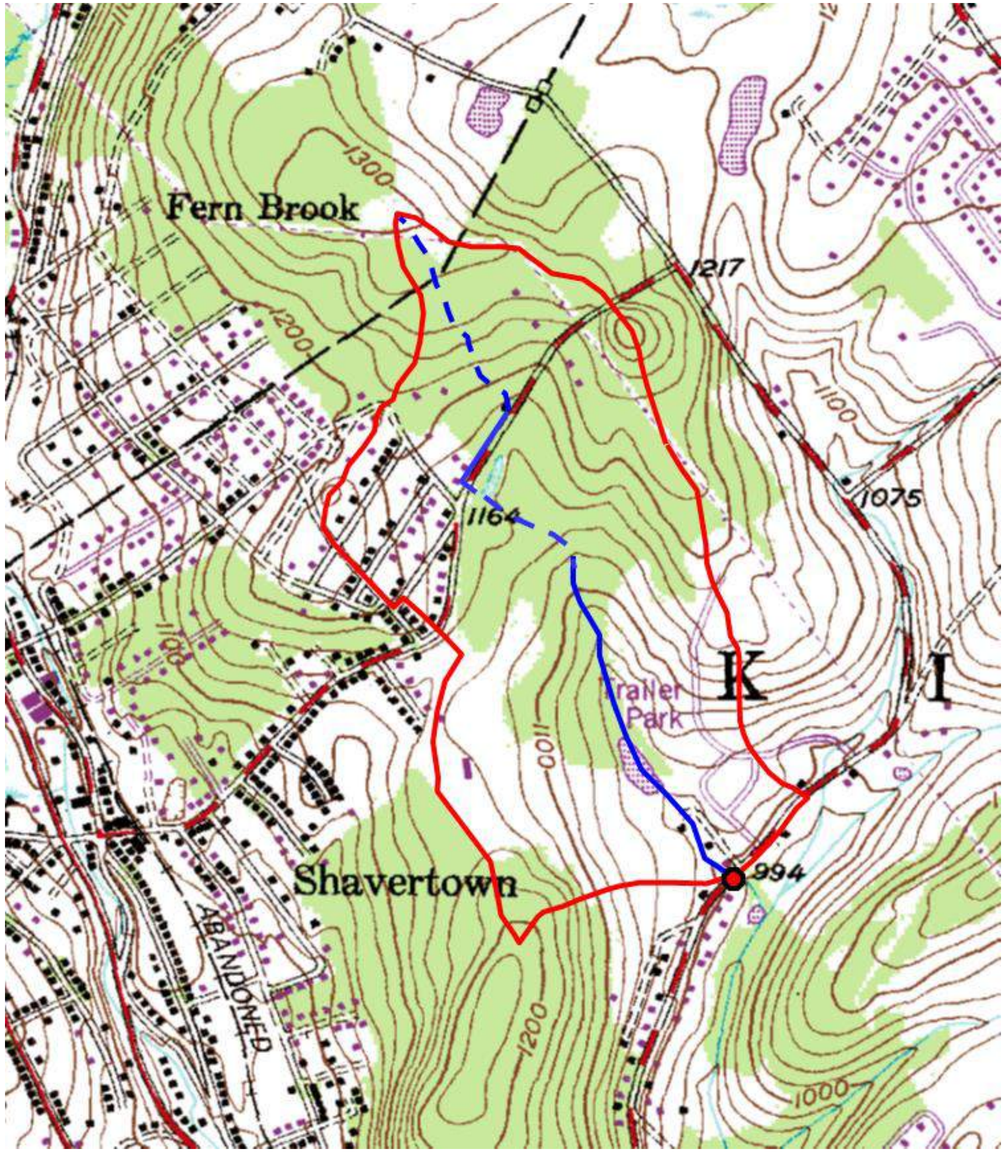
… plus three others.

3. In-channel

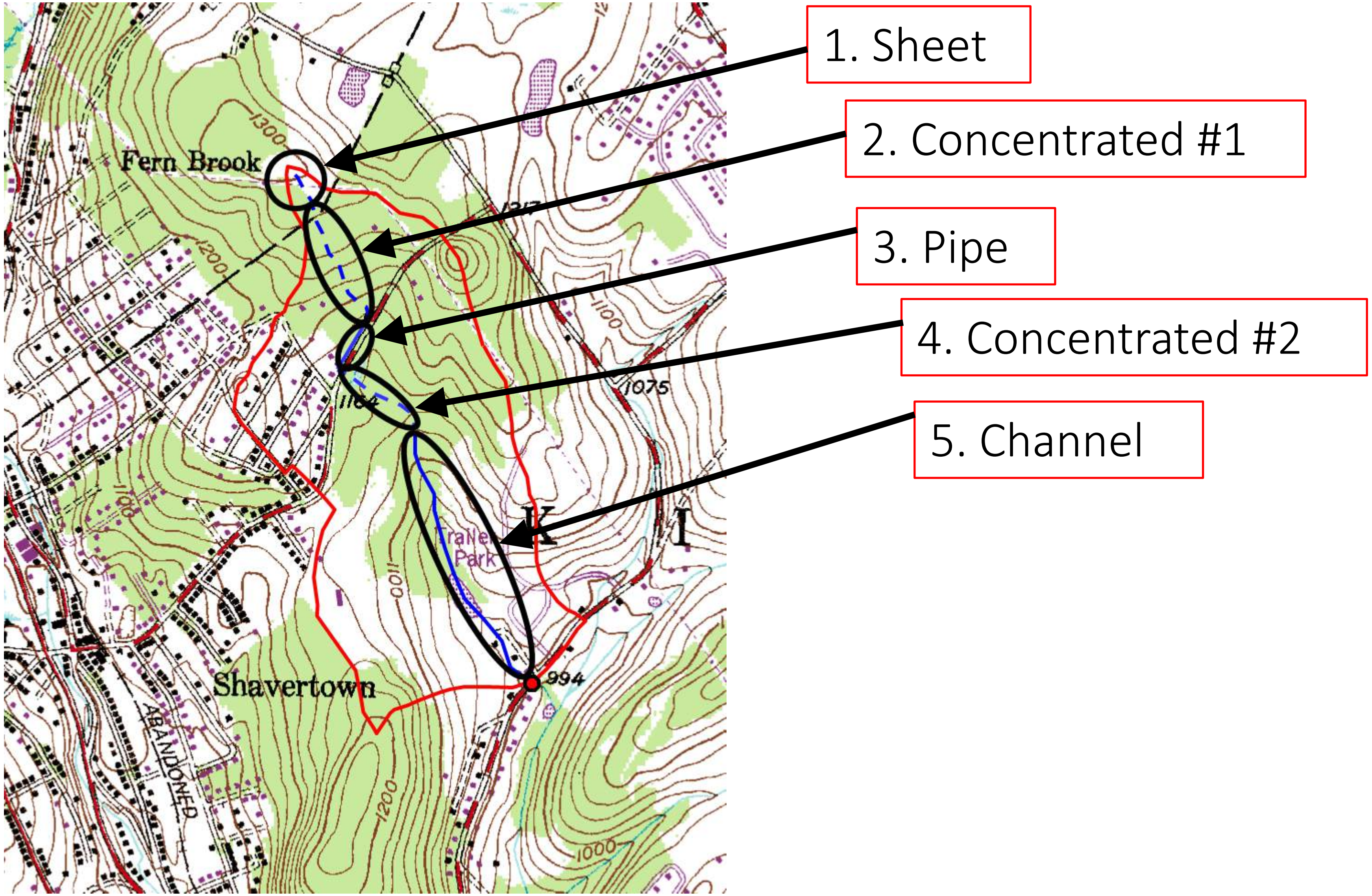
$$T = \frac{nL}{89.2\,R_h^{0.67}\,S^{0.5}}$$

Workshop Practice 2:

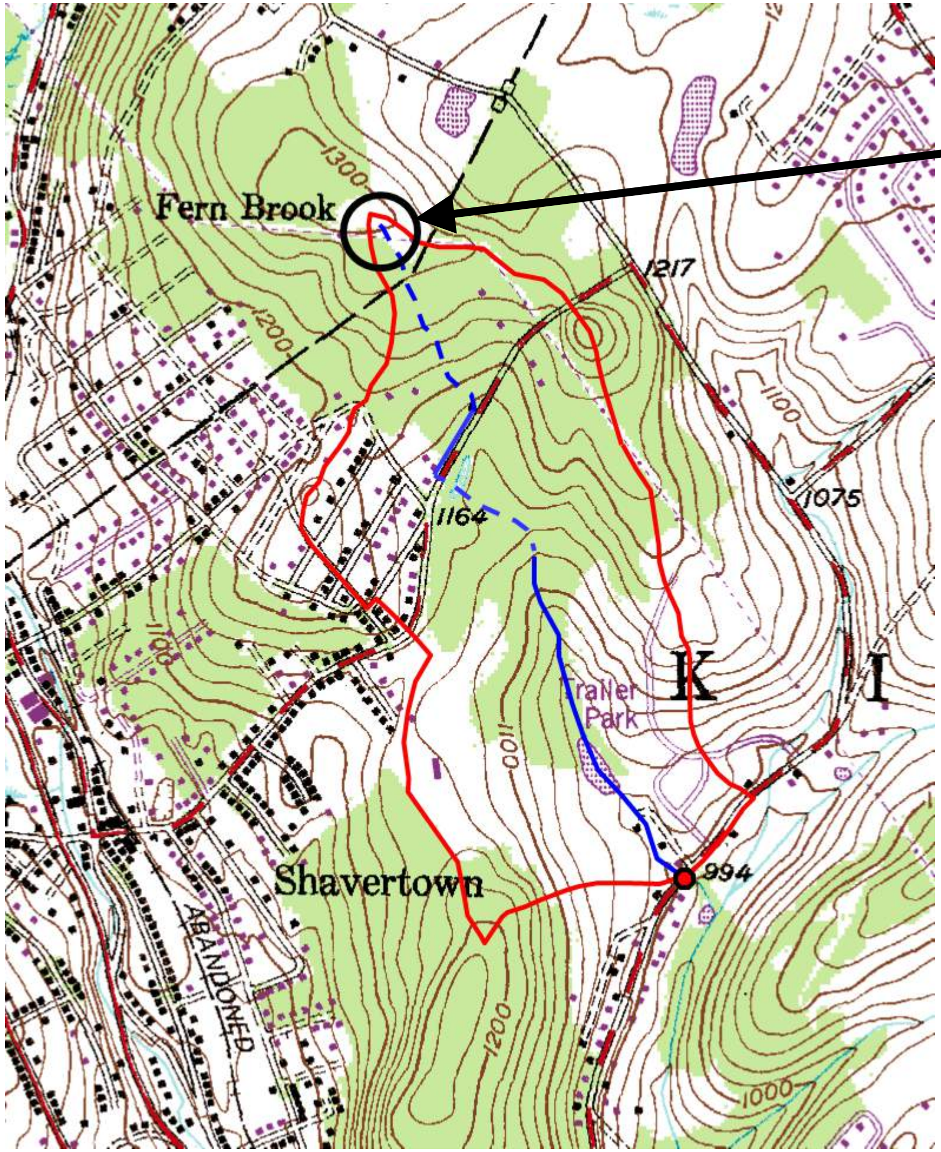
- Compute time of concentration for the Echo Valley watershed with the data provided on the following pages.



Echo Valley Watershed – Five Flow Segments



ECHO VALLEY WATERSHED



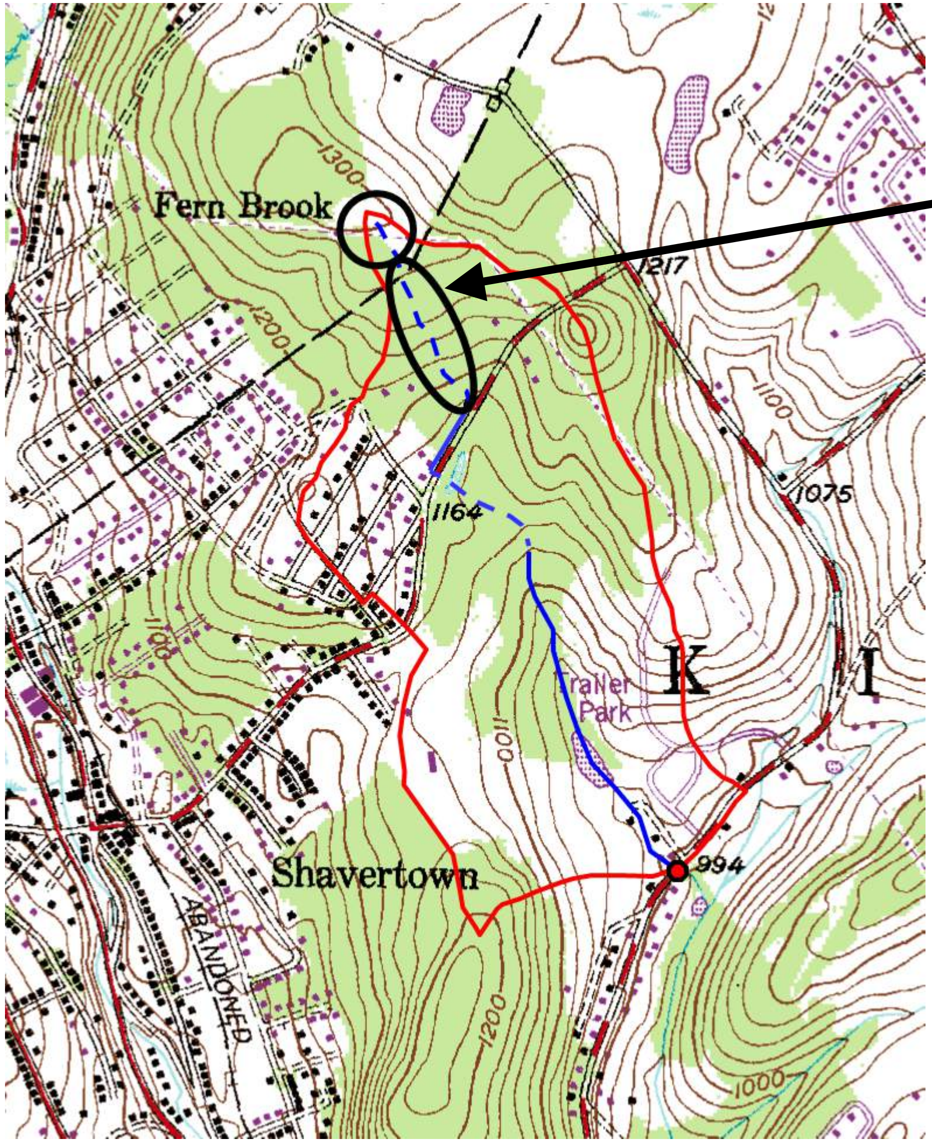
1. Sheet Flow Segment
L = 65 ft
S = 0.019 ft/ft
Dense grass
$_{2}P_{24}$ = 2.68 in (Pub. 584)

$$T = \frac{0.42}{P_2^{0.5}}\left(\frac{nL}{S^{0.5}}\right)^{0.8}$$

n = 0.24 (Table 3.1 TR-55)

T_t = 11.3 minutes

Echo Valley Watershed

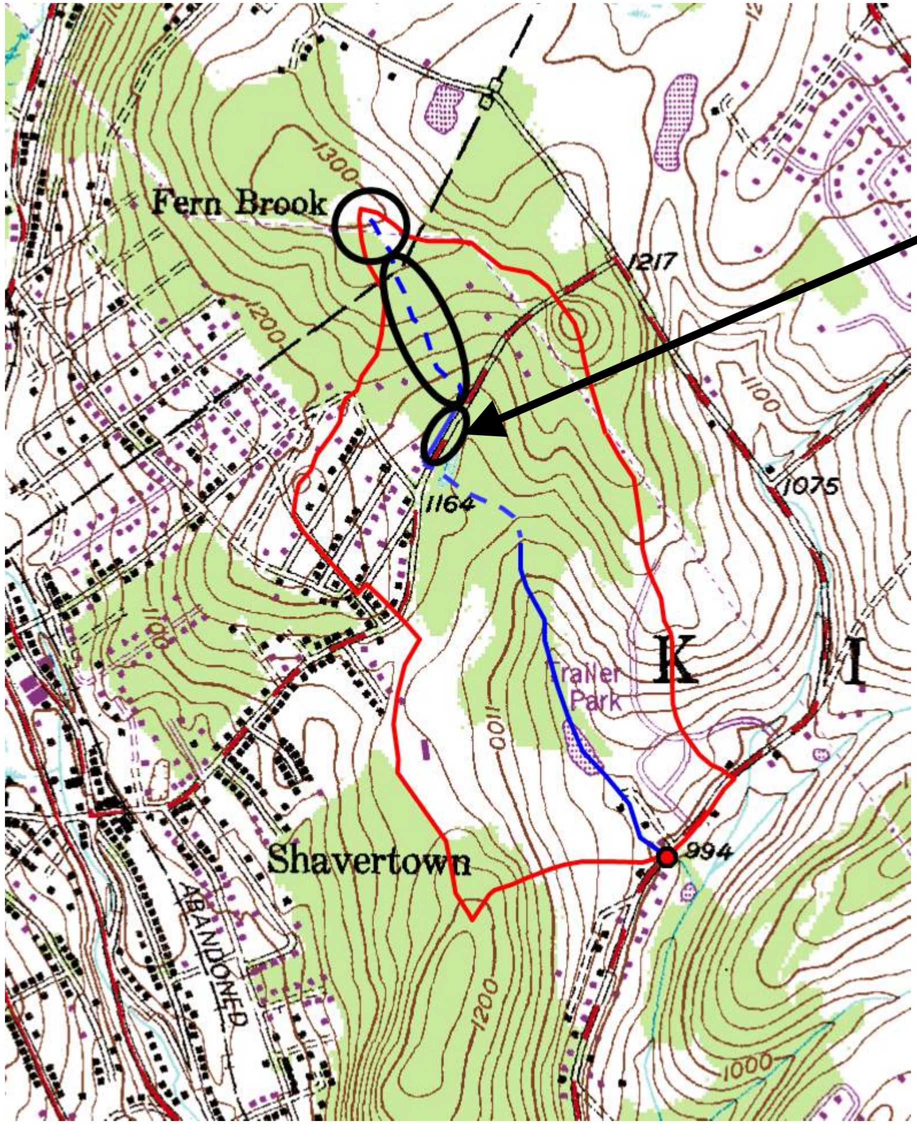


2. Concentrated Flow #1
L = 1080 ft
S = 0.103 ft/ft
Wooded

$$T_{\text{woodland}} = \frac{L}{302\,S^{0.5}}$$

T_t = 11.1 minutes

Echo Valley Watershed



3. Pipe Flow
L = 520 ft
S = 0.0185 ft/ft
18" Concrete Pipe (n = 0.013)

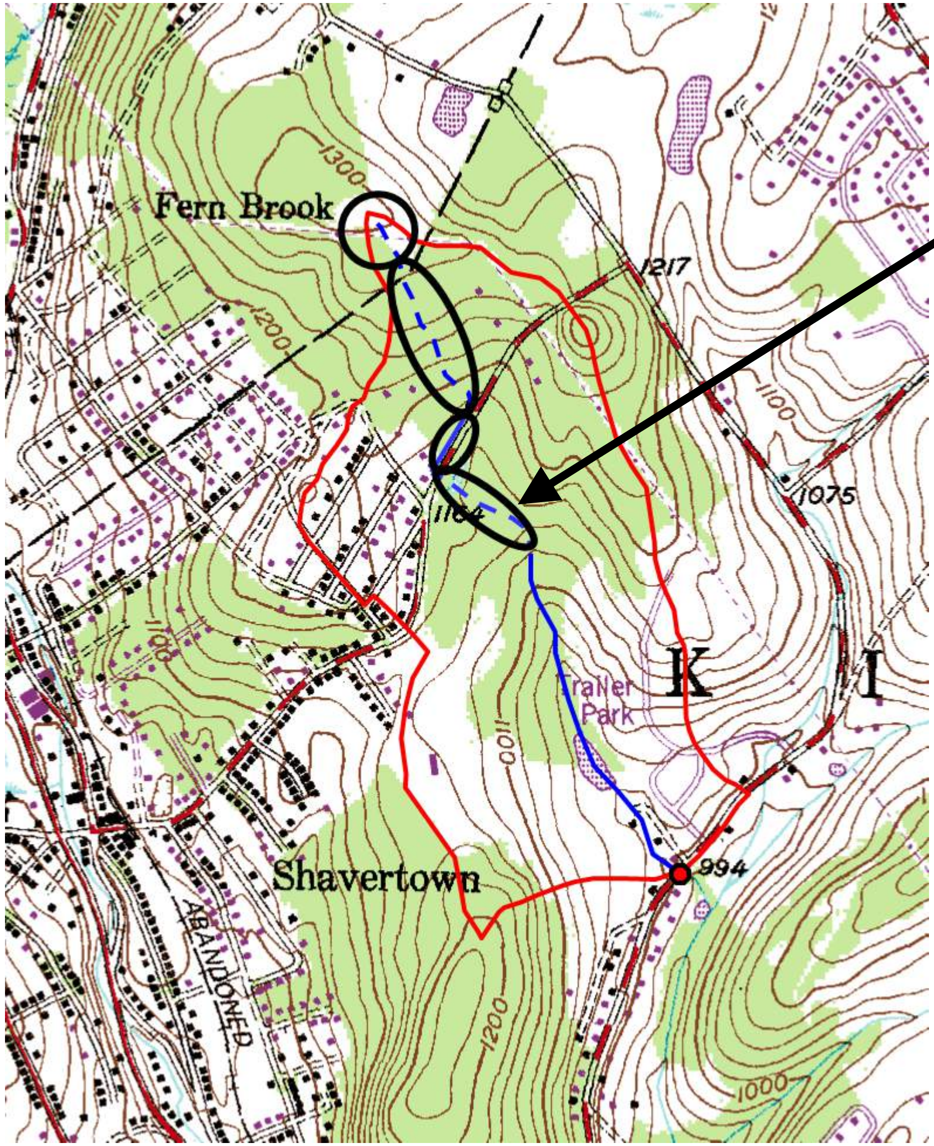
Manning's channel flow

$$T = \frac{nL}{89.2\ R_h^{0.67} S^{0.5}}$$

$$T_{\text{circ. pipe}} = \frac{nL}{35.4\ D^{0.67} S^{0.5}}$$

T_t = 1.1 minutes

ECHO VALLEY WATERSHED

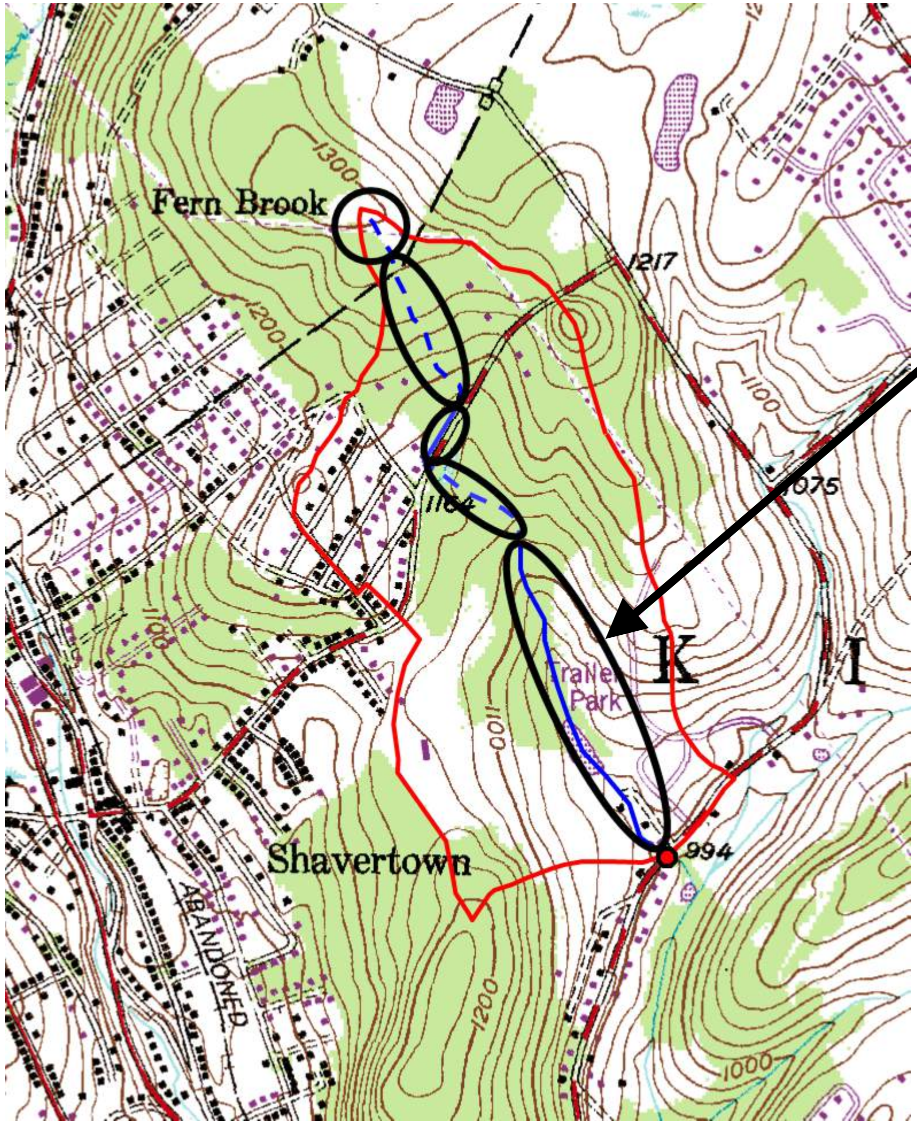


4. Concentrated Flow #2
L = 790 ft
S = 0.020 ft/ft
Grass waterway

$$T_{\text{grassed waterway}} = \frac{L}{968\,S^{0.5}}$$

T_t = 5.8 minutes

Echo Valley Watershed



5. Channel Flow

$A = 3.0\ ft^2$

$WP = 5.0\ ft$

$S = 0.066\ ft/ft$

$n = 0.035$

$L = 2500\ ft$

$$T = \frac{nL}{89.2\, R^{0.67} S^{0.5}}$$

T_t = 5.4 minutes

NRCS Segmental Method

- Echo Valley Watershed
  - Tc = T1 + T2 + T3 + T4 + T5
  - Tc = 11.3 + 11.1 + 1.1 + 5.8 + 5.4
  - **Tc = 34.7 minutes**

Rainfall Intensity

- Storm duration equals watershed time of concentration
- Select an appropriate data source
- PennDOT Pub. 584 or Atlas 14 are good choices for Pennsylvania

Workshop Practice 3:

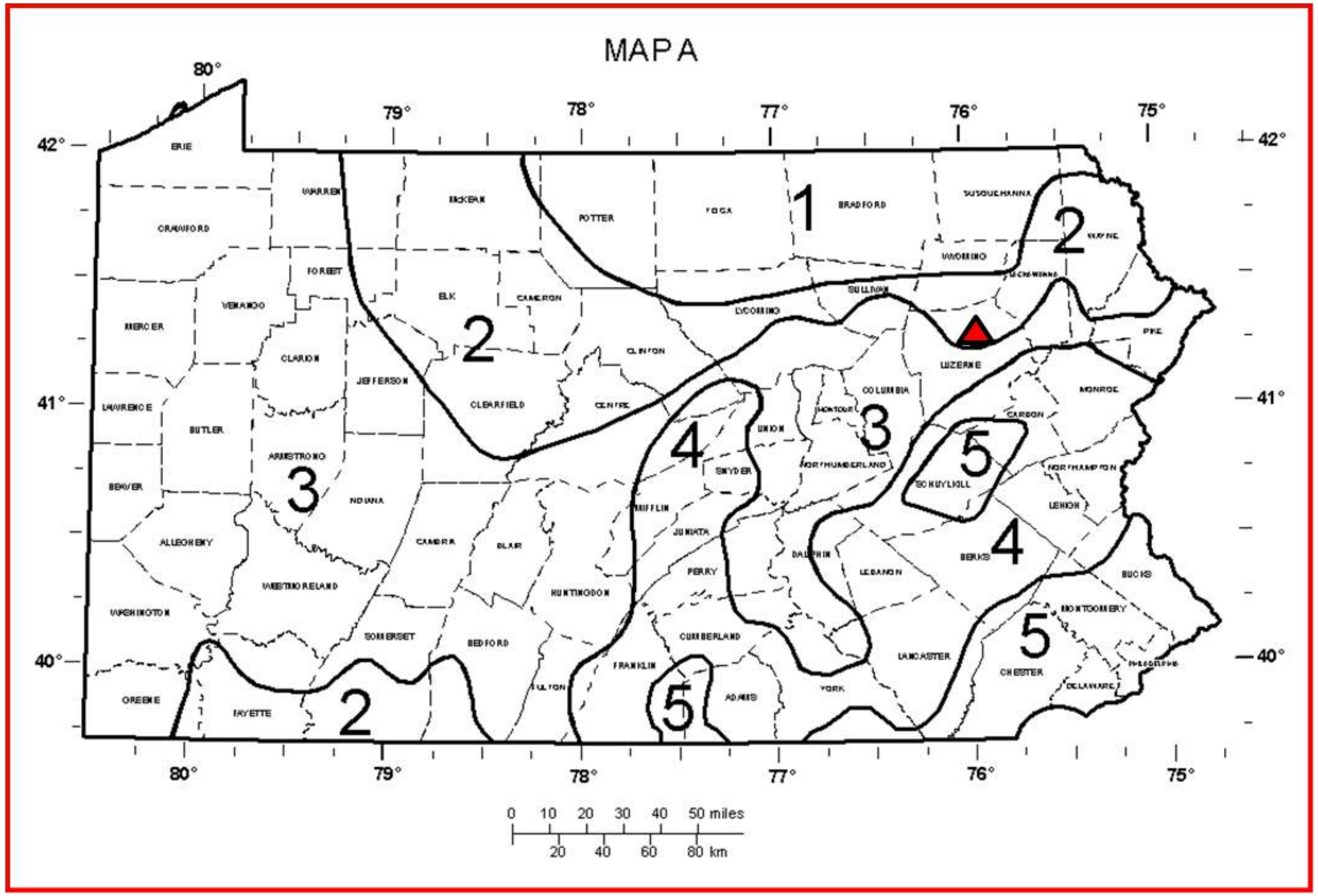
- Estimate the 10-yr rainfall intensity for Echo Valley Watershed using PennDOT Pub. 584

Table 7A.1 Appropriate Rainfall Region Map for each Storm Duration and Frequency

	Frequency							
Duration	**1 year**	**2 year**	**5 year**	**10 year**	**25 year**	**50 year**	**100 year**	**500 year**
5 min	C	C	C	C	B	B	B	-
10 min	C	C	C	C	C	C	C	-
15 min	A	A	A	A	C	C	C	-
30 min	A	A	A	A	A	C	C	-
60 min	A	A	A	A	A	C	C	-
2 hr	E	E	E	E	E	E	E	-
3 hr	E	E	E	E	E	E	E	-
6 hr	D	D	D	D	D	D	D	-
12 hr	F	F	F	F	F	F	F	-
24 hr	F	F	F	F	F	F	F	F

WORKSHOP PRACTICE 3:

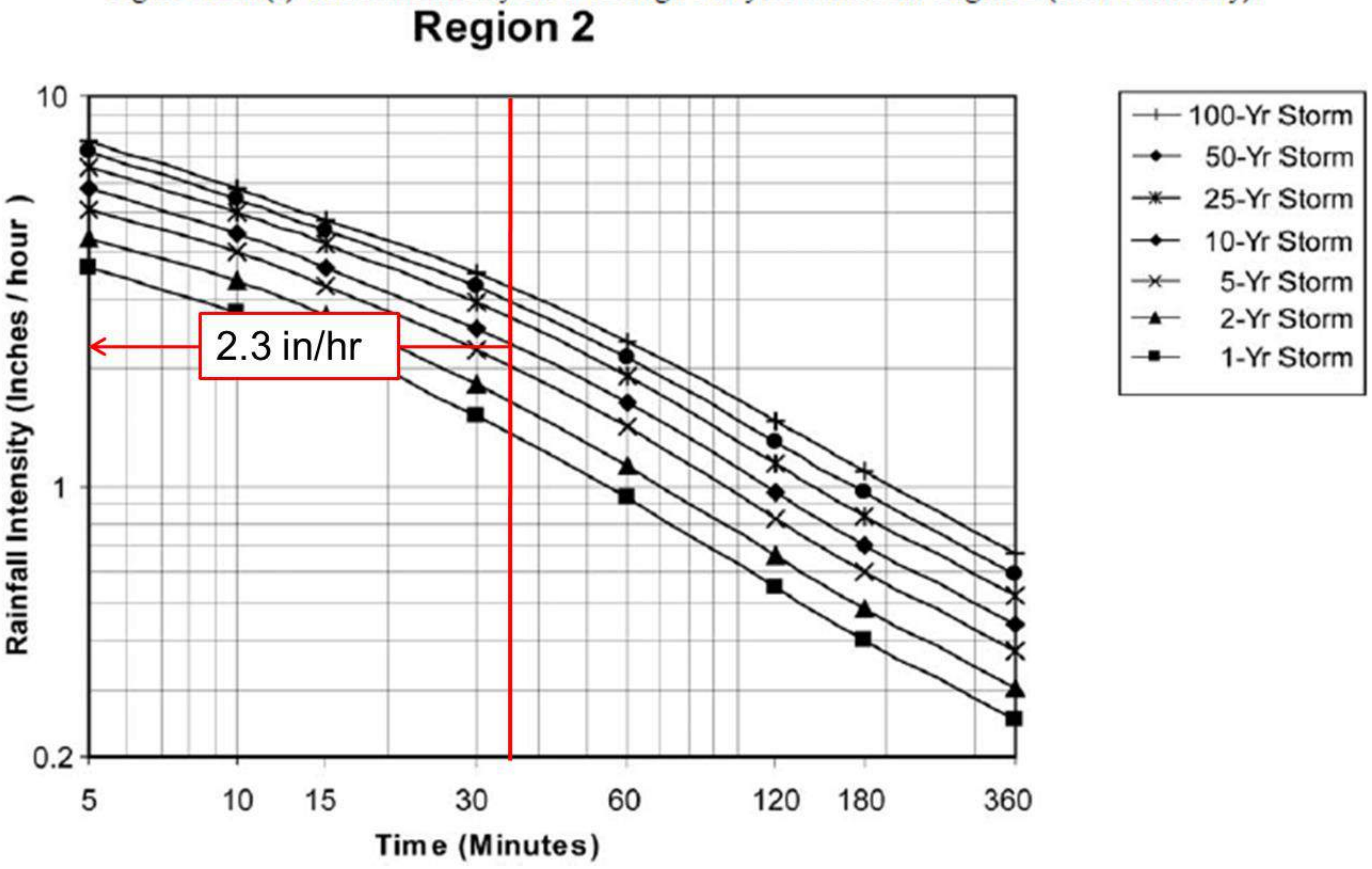
- Estimate the 10-yr rainfall intensity for Echo Valley Watershed using PennDOT Pub. 584



Region 2 for the 10-yr. event

REGION 2 IDF CURVE (INTENSITY)

Figure 7A.10(a) Rainfall Intensity for 1- through 100-year Storms for Region 2 (U.S. Customary).



Application of Rational for Echo Valley Watershed

$$\boxed{q = CiA}$$

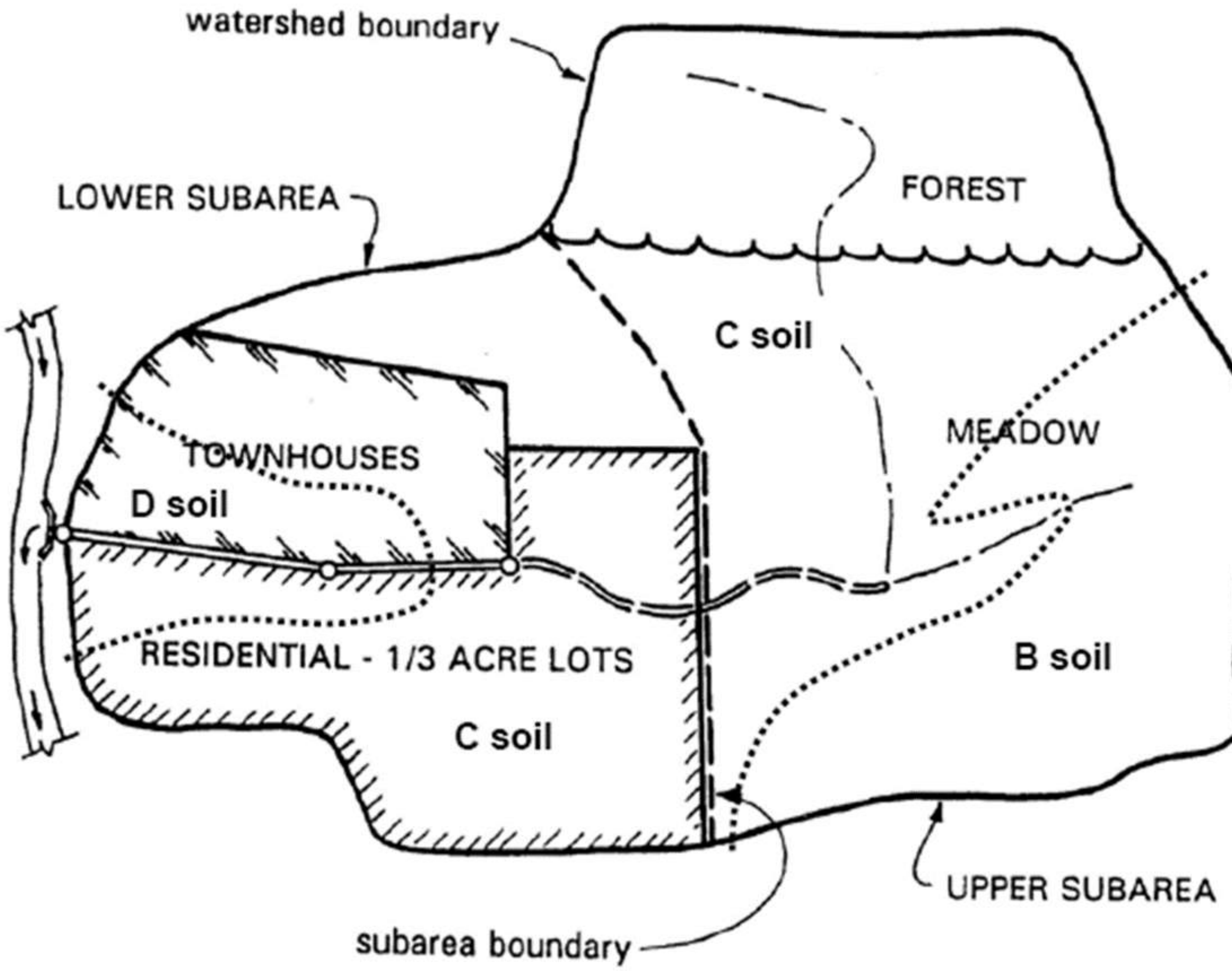
- Required input data:
- C = 0.26 (weighted C value)
- i = 2.3 in/hr. (storm duration of 34.9 minutes)
- A = 169 acres

$$\boxed{q = 101\ \mathrm{ft^3/s}}$$

Workshop Practice: Rational Formula

- Watershed Description
  - A watershed containing 182 acres located in Bradford, PA (McKean County)
  - Rain gage location: Bradford City Hall
  - Land use, soils data and timing information is provided
  - Use the Rational formula to compute the 25-yr peak flow

Bradford WS Land Use and Soils



Bradford WS Land Use & Soils

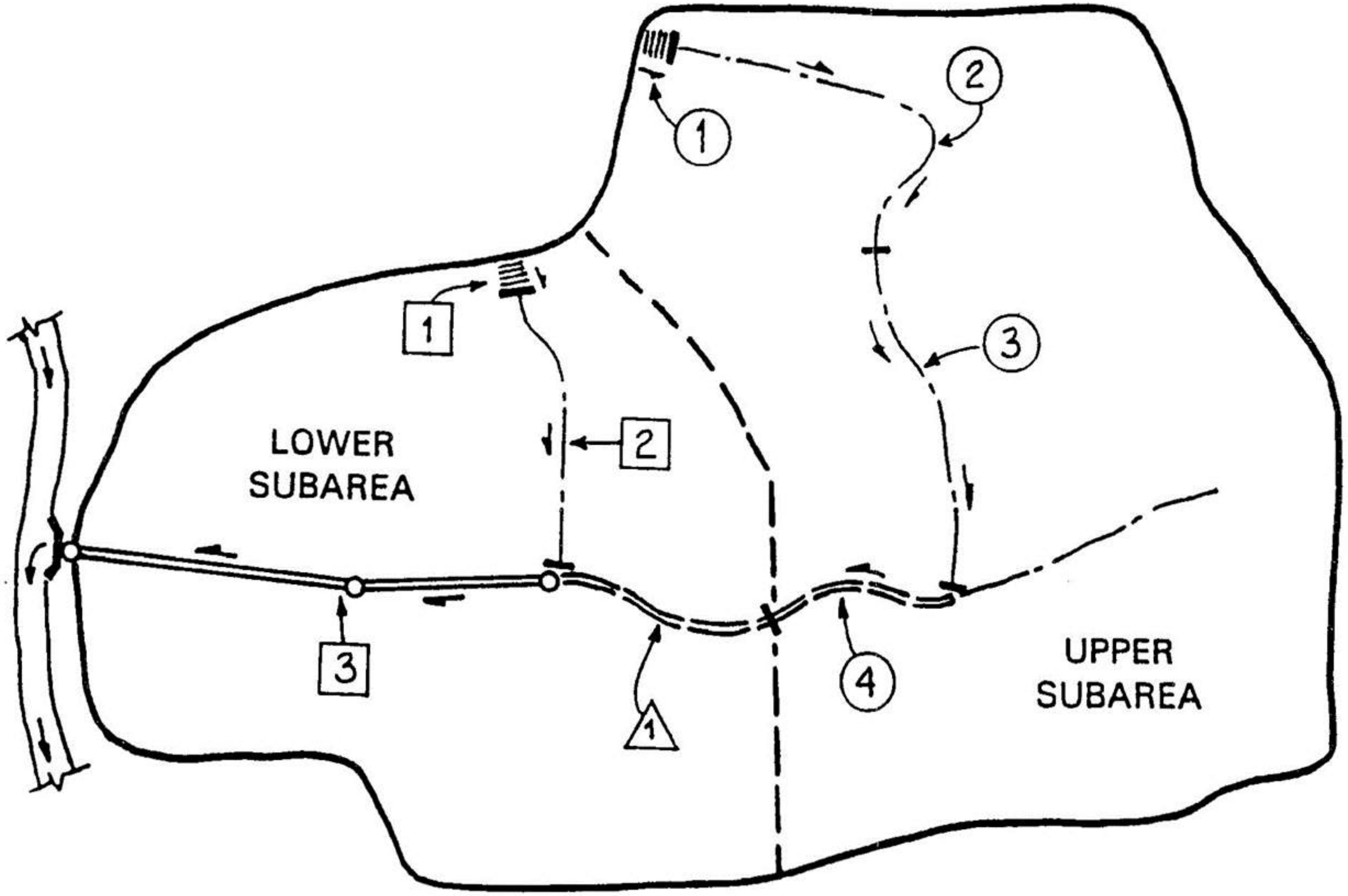
No.	Acres	Land Use	Condition	Surface Slope (%)	Hyd. Soil Group
1	30.5	Forest	Good	5.4	C
2	53.7	Meadow	Ungrazed	4.2	C
3	35.6	Meadow	Ungrazed	3.3	B
4	37.2	Residential 1/3 acre lots	-	1.5	C
5	5.7	Residential 1/3 acre lots	-	1.5	D
6	11.9	Townhouses 1/8 acre lots	-	1.0	C
7	7.7	Townhouses 1/8 acre lots	-	1.0	D
	182.3				

WEIGHTED C WORKSHEET

Land use	*C*	*A*	*C x A*
Forest		30.5	
Meadow		53.7	
Meadow		35.6	
Residential 1/3 acre lots		37.2	
Residential 1/3 acre lots		5.7	
Townhouses 1/8 acre lots		11.9	
Townhouses 1/8 acre lots		7.7	
		182.3	

$$C_{weighted} = \frac{\qquad}{\qquad} = \frac{\qquad}{\qquad}$$

BRADFORD WS TRAVEL TIME DATA



Bradford WS Travel Time Data

Path	Type	L (ft)	S (ft/ft)	Description
○-1	Sheet	40	0.061	Woods with light underbrush
○-2	Concentrated	1500	0.055	Woods with little under brush, nearly bare ground along region of flow path
○-3	Concentrated	1280	0.031	Grassy swale through meadow and light brush, almost a grassed waterway
○-4	Natural channel	750	0.025	bankfull, $d \approx 1.0$ ft, $b \approx 2.0$ ft, $z \approx 1{:}1$, $n = 0.035$
Δ-1	Natural channel	780	0.010	bankfull, $d \approx 1.0$ ft, $b \approx 3.0$ ft, $z \approx 2{:}1$, $n = 0.035$
□-3	Closed conduit	1620	0.010	48” reinforced concrete pipe, $n = 0.013$

Travel Time Worksheet

Path	Type	L (ft)	S (ft/ft)	n or surface description	Travel time (minutes)
○-1	Sheet ($P_{2,24}$ = 2.45")	40	0.061		
○-2	Concentrated	1500	0.055		
○-3	Concentrated	1280	0.031		
○-4	Natural channel	750	0.025		
Δ-1	Natural channel	780	0.010		
□-3	Closed conduit	1620	0.010		
	Time of concentration	-	-	-	

ATLAS 14: BRADFORD CITY HALL

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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
5-min	**3.55** (3.20-3.92)	**4.22** (3.82-4.67)	**5.12** (4.62-5.65)	**5.82** (5.24-6.40)	**6.70** (6.01-7.34)	**7.37** (6.60-8.08)	**8.02** (7.15-8.78)	**8.69** (7.73-9.49)	**9.58** (8.46-10.5)
10-min	**2.76** (2.50-3.05)	**3.30** (2.98-3.65)	**3.98** (3.59-4.39)	**4.49** (4.05-4.93)	**5.12** (4.60-5.62)	**5.59** (5.00-6.12)	**6.04** (5.38-6.61)	**6.48** (5.77-7.09)	**7.04** (6.22-7.68)
15-min	**2.26** (2.04-2.49)	**2.69** (2.43-2.97)	**3.26** (2.94-3.59)	**3.68** (3.32-4.04)	**4.22** (3.78-4.63)	**4.61** (4.12-5.05)	**5.00** (4.46-5.47)	**5.38** (4.78-5.88)	**5.86** (5.17-6.39)
30-min	**1.49** (1.35-1.65)	**1.80** (1.63-1.99)	**2.23** (2.01-2.46)	**2.56** (2.31-2.81)	**2.98** (2.67-3.27)	**3.29** (2.95-3.61)	**3.61** (3.22-3.95)	**3.92** (3.49-4.29)	**4.34** (3.83-4.73)
60-min	**0.911** (0.823-1.01)	**1.11** (0.997-1.22)	**1.40** (1.26-1.54)	**1.63** (1.47-1.79)	**1.93** (1.73-2.12)	**2.17** (1.94-2.38)	**2.41** (2.15-2.64)	**2.66** (2.37-2.91)	**3.00** (2.65-3.27)
2-hr	**0.533** (0.483-0.588)	**0.646** (0.586-0.714)	**0.814** (0.738-0.898)	**0.946** (0.855-1.04)	**1.13** (1.02-1.24)	**1.27** (1.14-1.40)	**1.42** (1.27-1.56)	**1.58** (1.40-1.73)	**1.80** (1.58-1.96)
3-hr	**0.388** (0.351-0.431)	**0.469** (0.425-0.520)	**0.589** (0.533-0.654)	**0.685** (0.618-0.759)	**0.819** (0.735-0.903)	**0.926** (0.828-1.02)	**1.04** (0.924-1.14)	**1.16** (1.02-1.27)	**1.32** (1.16-1.44)
6-hr	**0.238** (0.217-0.266)	**0.287** (0.261-0.320)	**0.358** (0.325-0.397)	**0.415** (0.376-0.460)	**0.496** (0.448-0.548)	**0.562** (0.504-0.619)	**0.632** (0.564-0.694)	**0.706** (0.626-0.773)	**0.810** (0.712-0.885)
12-hr	**0.144** (0.131-0.159)	**0.172** (0.157-0.190)	**0.212** (0.194-0.234)	**0.245** (0.223-0.270)	**0.293** (0.265-0.322)	**0.332** (0.299-0.364)	**0.374** (0.335-0.408)	**0.419** (0.372-0.456)	**0.483** (0.424-0.523)
24-hr	**0.086** (0.080-0.092)	**0.102** (0.095-0.110)	**0.125** (0.116-0.134)	**0.143** (0.134-0.154)	**0.170** (0.158-0.182)	**0.192** (0.177-0.205)	**0.215** (0.198-0.229)	**0.239** (0.219-0.255)	**0.274** (0.249-0.291)

25-yr Peak Flow

- C =
- i (in/hr) =
- A (acres) =
- q (ft^3/s) =

WEIGHTED C WORKSHEET

Land use	*C*	*A*	*C x A*
Forest	0.16	30.5	4.88
Meadow	0.35	53.7	18.80
Meadow	0.28	35.6	9.97
Residential 1/3 acre lots	0.33	37.2	12.28
Residential 1/3 acre lots	0.36	5.7	2.05
Townhouses 1/8 acre lots	0.38	11.9	4.52
Townhouses 1/8 acre lots	0.41	7.7	3.16
		182.3	55.65

$$C_{weighted} = \frac{55.65}{182.3} = \underline{0.305}$$

Travel Time Worksheet

Path	Type	L (ft)	S (ft/ft)	n or surface description	Travel time (minutes)
O-1	Sheet ($P_{2,24}$ = 2.45”)	40	0.011	0.40	7.55
O-2	Concentrated	1500	0.055	Nearly bare ground	10.77
O-3	Concentrated	1280	0.031	Grassed waterway	7.97
O-4	Natural channel	750	0.025	0.035	2.56
Δ-1	Natural channel	780	0.010	0.035	4.00
□-3	Closed conduit	1620	0.010	0.013	2.36
	Time of concentration	-	-	-	35.21

25-YR RAINFALL INTENSITY

- From Atlas 14: at 30 minutes i = 2.98 in/hr
- at 60 minutes i = 1.93 in/hr

- Interpolate between these two intensities to get i for tc = 35.2 minutes.

$$i_{35.2} = 2.98 - \frac{(35.2-30)}{(60-30)}(2.98-1.93) = 2.80 \text{ in/hr}$$

25-YR PEAK FLOW

- C = 0.305
- i (in/hr) = 2.80 in/hr
- A (acres) = 182.3 acres
- q (ft^3/s) = 155.7 ft^3/s

Manning's Equation for Swale Design

MANNING'S EQUATION

- Velocity Form
  - Flow velocity in an open channel with a uniform section geometry and steady flow condition is

$$\boxed{v = \frac{1.49}{n} R_h^{2/3} S^{1/2}}$$

v = *channel velocity (ft/s)*

n = *channel roughness (flow resistance) factor*

R_h = *hydraulic radius*

S = *channel bottom slope in units of ft/ft*

CONCRETE LINED OPEN CHANNEL USED IN IRRIGATION

ROUGHNESS VALUES, n

Pennoni

- For open Channels

Surface Type	*n*
Glass, copper, or other smooth surfaces	0.010
Smooth unpainted steel, planed wood	0.012
Smooth asphalt, finished concrete, glazed clay or brick	0.013
Uncoated cast iron, wrought iron, vitrified clay tile	0.014
Brick in cement mortar, float finished concrete	0.015
Rough concrete	0.017
Smooth excavated earth	0.022
Corrugated metal culverts	0.024
Grassy channel beds	0.030
Gravel channel beds	0.035
Rock channel beds	0.040 to 0.075
Light brush	0.050
Heavy brush	0.100 to 0.200

ROUGHNESS VALUES, n

- For closed conduits (open channel flow)

Surface Type	*n*
CLOSED CONDUITS	
Asbestos-cement pipe	0.011 – 0.015
Brick	0.013 – 0.017
Cast iron pipe	
Cement lined and seal coated	0.011 – 0.015
Concrete (monolithic)	
Smooth forms	0.012 – 0.014
Rough forms	0.015 – 0.017
Concrete pipe	0.011 – 0.015
Corrugated metal pipe	
½ inch x 2 ½ inch corrugations	
Plain	0.022 – 0.026
Paved invert	0.018 – 0.022
Spun asphalt lined	0.011 – 0.015
Plastic pipe (smooth)	0.011 – 0.015
Vitrified clay	
Pipes	0.011 – 0.015
Liner plates	0.013 – 0.017

Roughness Values, n

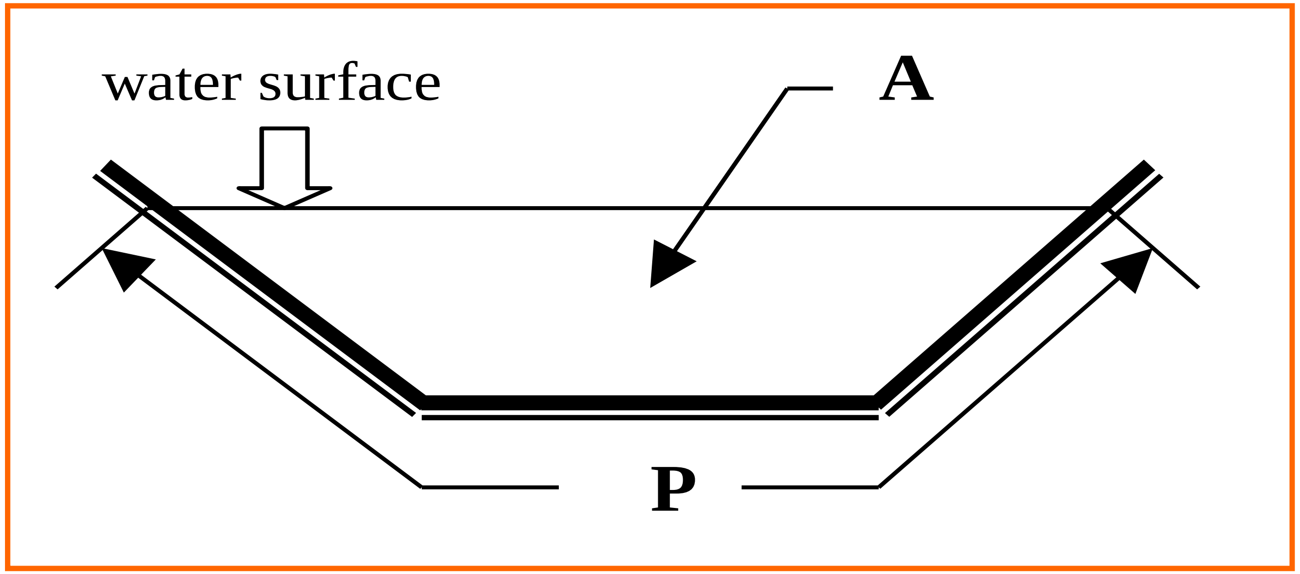
Other sources for Manning's n values:

- AISI, Modern Sewer Design, 4th Edition, 1999.
- ASCE, Design and Construction of Urban Stormwater Management Systems, 1992.
- Chow, V. T. Handbook of Hydraulics, McGraw-Hill, 1959.
- Seybert, T. A. Stormwater Management for Land Development, 2nd Edition, Amazon, 2018.

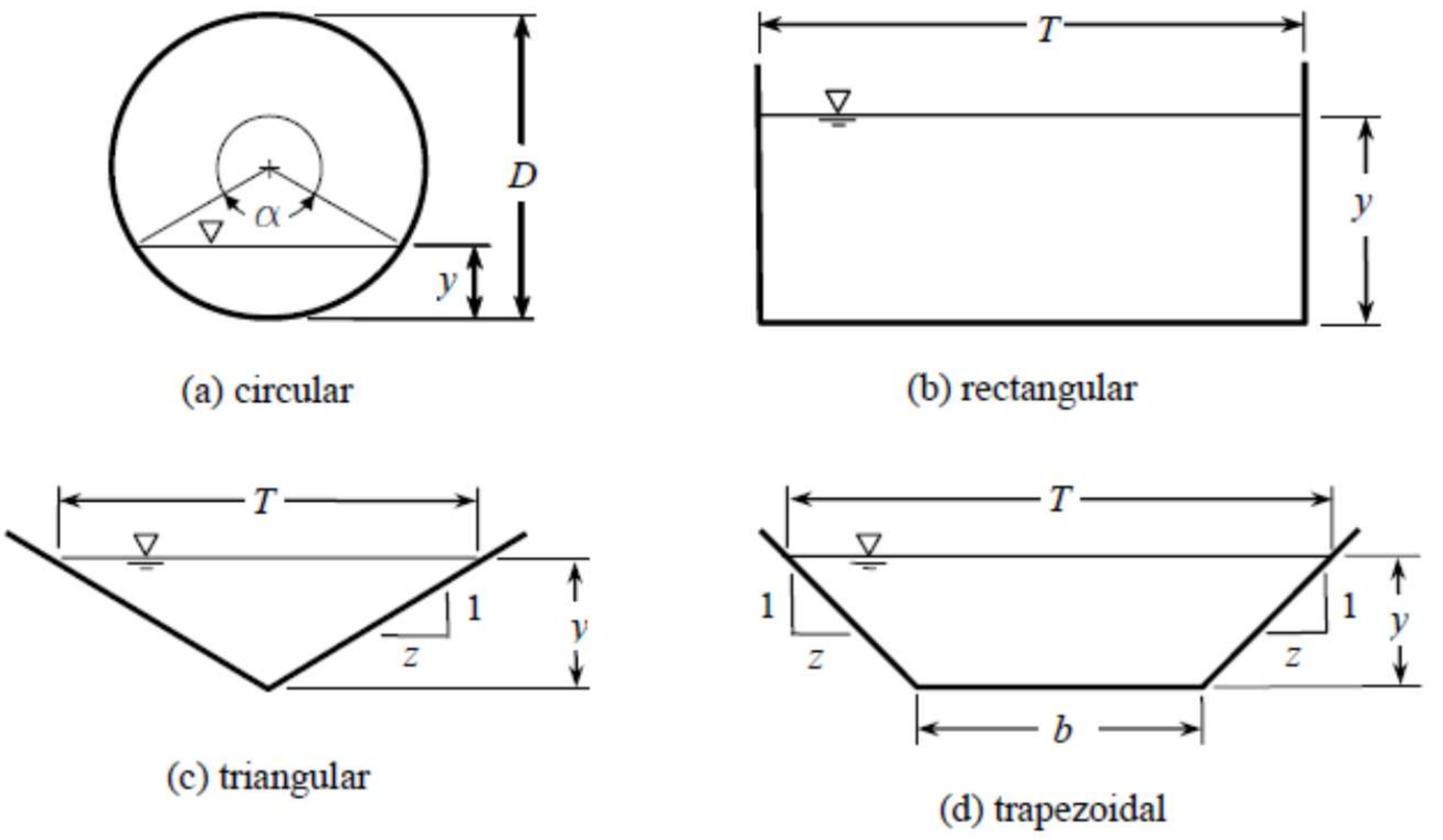
HYDRAULIC RADIUS

$$v = \frac{1.49}{n} R_h^{2/3} S^{1/2}$$

$$R_h = \frac{A}{P} = \frac{\text{flow area}}{\text{wetted perimeter of flow area}}$$



Typical section geometries for open channels



ANALYZING CHANNEL FLOW CAPACITY

- Use the flow rate form of the equation
- The most commonly used form

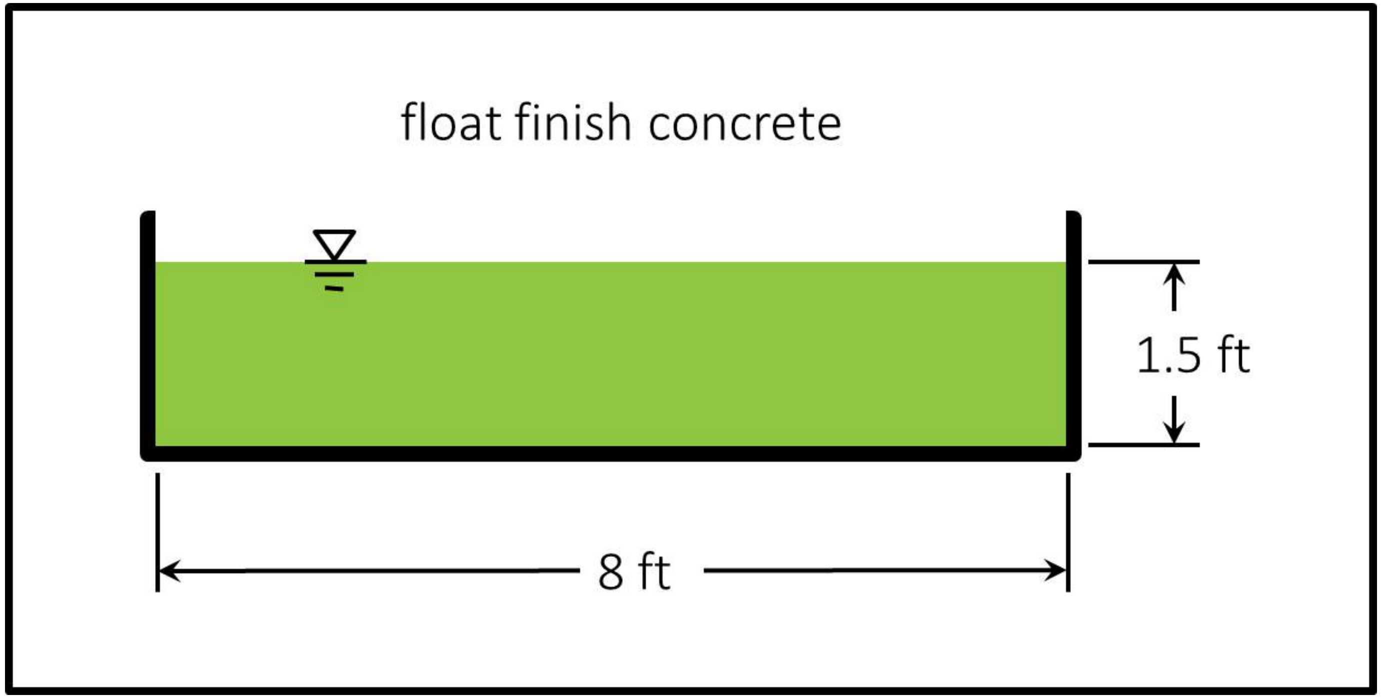
If flow rate is $q = vA$

then Manning's can be rewritten as …

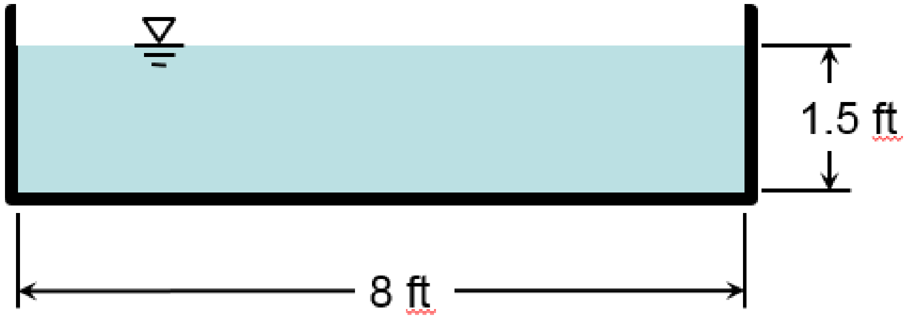
$$\boxed{q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}}$$

EXAMPLE 1:

- Compute the flow in a rectangular concrete channel (float finish) having bottom width of 8 ft, flow depth of 1.5 ft, and bed slope of 1 ft in 130 ft.



Example 1: To start, select n; compute flow area, wetted perimeter and hydraulic radius.



- Roughness, n: float finish concrete is about 0.015
- Flow area: $A = by = (8\text{ ft})(1.5\text{ ft}) = 12\text{ ft}^2$
- Wetted perimeter: $P = b + 2y = 8 + 2(1.5) = 11\text{ ft}$
- Hydraulic Radius: $R_h = \dfrac{A}{P} = \dfrac{12\text{ ft}^2}{11\text{ ft}} = 1.091\text{ ft}$

Example 1: Continue; compute slope and flow rate

- Slope: $$S = \frac{\Delta Elev}{L} = \frac{1 \text{ ft}}{130 \text{ ft}} = 0.00769 \text{ ft/ft}$$

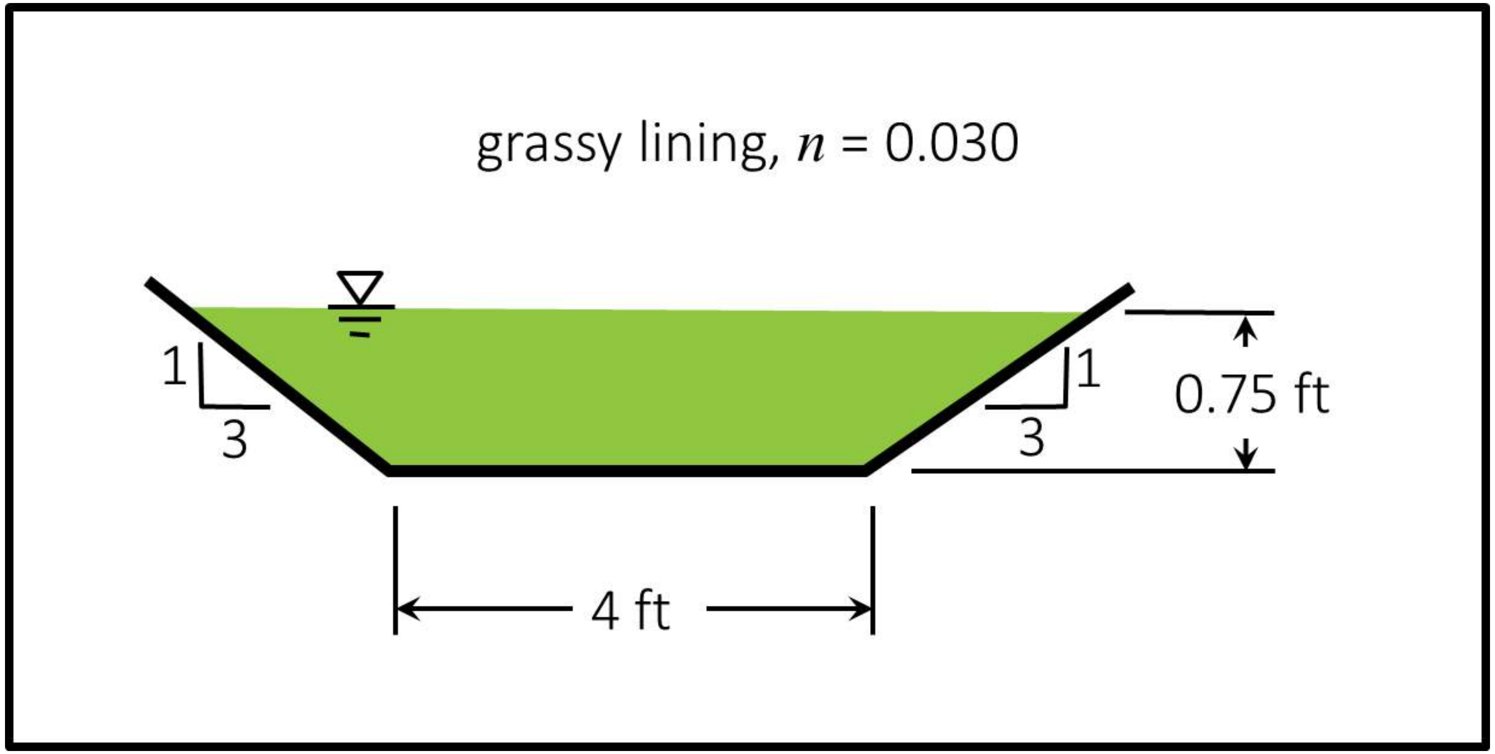
- Flow rate: $$q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}$$

$$q = \frac{1.49}{0.015}\left(12 \text{ ft}^2\right)\left(1.091 \text{ ft}\right)^{2/3}\left(0.00769 \text{ ft/ft}\right)^{1/2}$$

$$\boxed{q = 110.8 \text{ ft}^3/\text{s}}$$

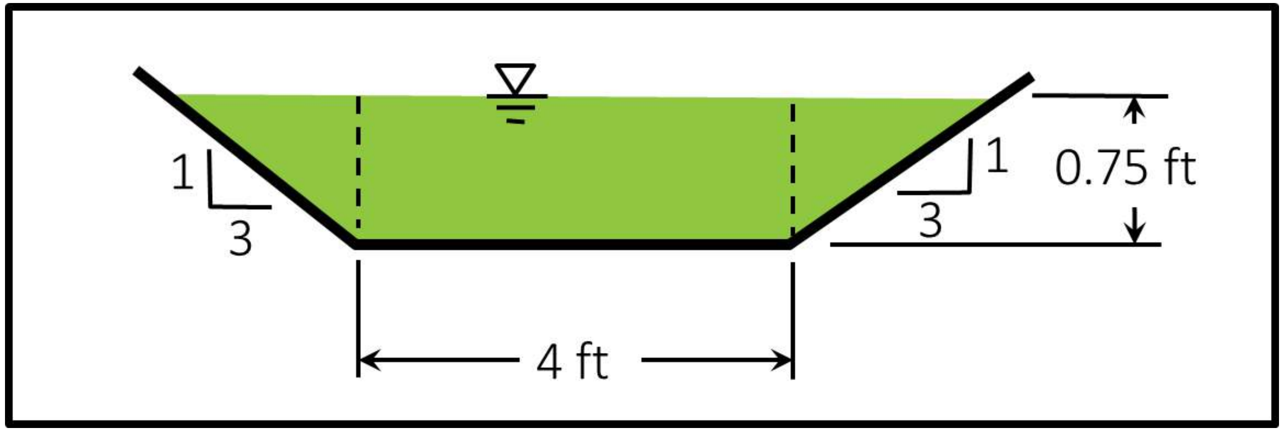
EXAMPLE 2:

- Compute the flow in a grassy trapezoidal channel having bottom width of 4 ft, side slopes of 3H:1V, flow depth of 0.75 ft, and bed slope of 1 ft in 90 ft.



EXAMPLE 2:

- Compute the flow area and wetted perimeter using basic geometry. Remember that n = 0.030



- Flow area: $A=(4)(0.75)+2\left(\frac{1}{2}(3)\left(0.75\right)\times\left(0.75\right)\right)=4.69\text{ ft}^2$

- Wetted Perimeter: $P=4+2\sqrt{0.75^2+\left(3\times 0.75\right)^2}=8.74\text{ ft}$

Example 2: Compute the hydraulic radius, slope and flow rate

- Hydraulic Radius: $R_h = \dfrac{A}{P} = \dfrac{4.69}{8.74} = 0.537 \text{ ft}$

- Slope: $S = \dfrac{\Delta Elev}{L} = \dfrac{1}{90} = 0.0111 \text{ ft/ft}$

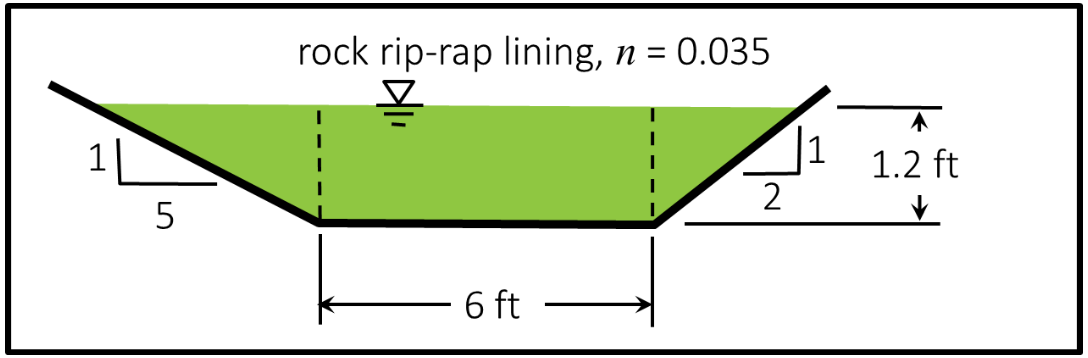
- Flow Rate: $q = \dfrac{1.49}{n} A R_h^{2/3} S^{1/2}$

$$q = \frac{1.49}{0.030}\left(4.69 \text{ ft}^2\right)\left(0.537 \text{ ft}\right)^{2/3}\left(0.0111 \text{ ft/ft}\right)^{1/2}$$

$$\boxed{q = 16.22 \text{ ft}^3/\text{s}}$$

Example 3:

- Compute the flow in a rock rip-rap lined trapezoidal channel (n = 0.035) having bottom width of 6 ft, side slopes of 5H:1V, on the left, 2H:1V on the right, flow depth of 1.2 ft and bed slope of 1 ft in 75 ft.



$$A = \left(\frac{1}{2}(5)(1.2)(1.2)\right) + (6)(1.2) + \left(\frac{1}{2}(2)(1.2)(1.2)\right) = 12.24 \text{ ft}^2$$

$$P = \sqrt{1.2^2 + (5\times1.2)^2} + 6 + \sqrt{1.2^2 + (2\times1.2)^2} = 14.80 \text{ ft}$$

EXAMPLE 3:

- Compute the hydraulic radius, slope and flow rate. Note roughness n = 0.035
  - Hydraulic Radius: $R_h = \frac{A}{P} = \frac{12.24}{14.80} = 0.827\ \text{ft}$
  - Slope: $S = \frac{\Delta Elev}{L} = \frac{1}{75} = 0.01333\ \text{ft/ft}$
  - Flow rate: $q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}$

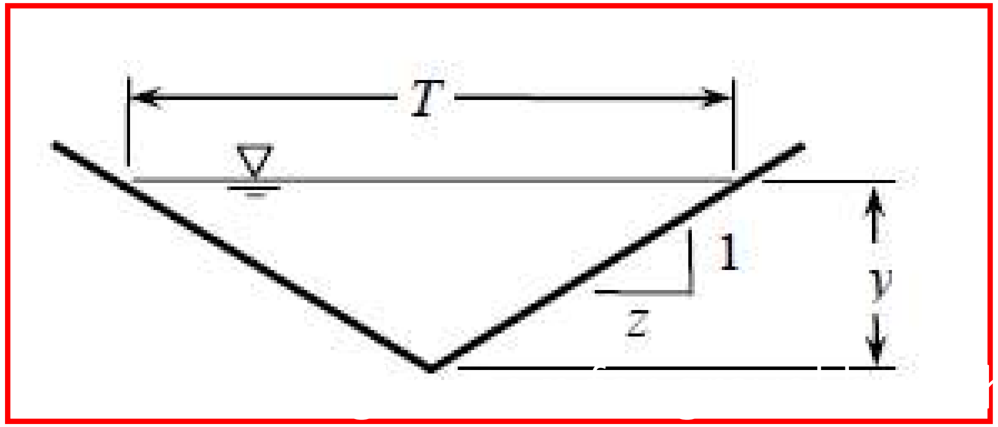
$$q = \frac{1.49}{0.035}\left(12.24\ \text{ft}^2\right)\left(0.827\ \text{ft}\right)^{2/3}\left(0.01333\ \text{ft/ft}\right)^{1/2}$$

$$\boxed{q = 53.0\ \text{ft}^3/\text{s}}$$

Workshop Practice 4:

Pennoni

- Compute the flow in a v-shaped gravel bed channel having side slopes of 5H:1V, center-line flow depth of 15 inches, length of 1200 ft and elevation drop of 25 ft.

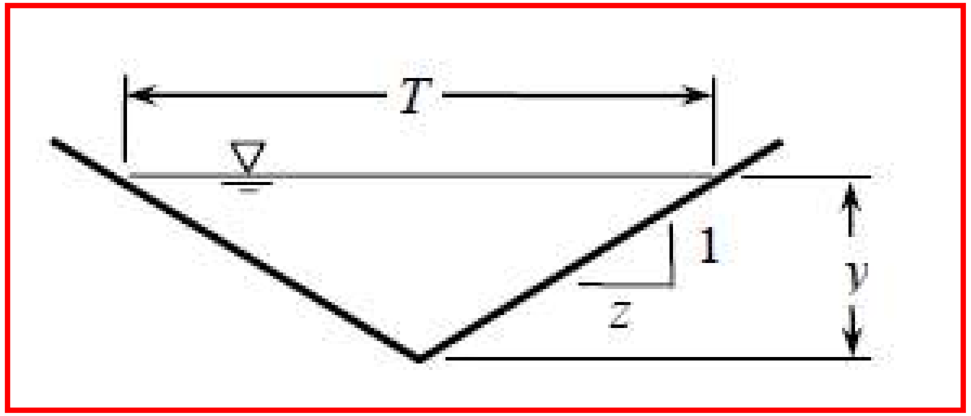


$$A = z(y)^2$$

$$P = 2\sqrt{y^2 + (zy)^2}$$

Workshop Practice 4:

- Solution



- Flow area: $A = z(y)^2 = 5(1.25)^2 = 7.81\ \text{ft}^2$

- Wetted perimeter: $P = 2\sqrt{y^2 + (zy)^2}$

$$P = 2\sqrt{1.25^2 + (5 \times 1.25)^2} = 12.75\ \text{ft}$$

- Hydraulic Radius: $R_h = \dfrac{A}{P} = \dfrac{7.81}{12.75} = 0.613\ \text{ft}$

Workshop Practice 4: Continued …

- Slope: $$S = \frac{\Delta Elev}{L} = \frac{25}{1200} = 0.0208 \text{ ft/ft}$$

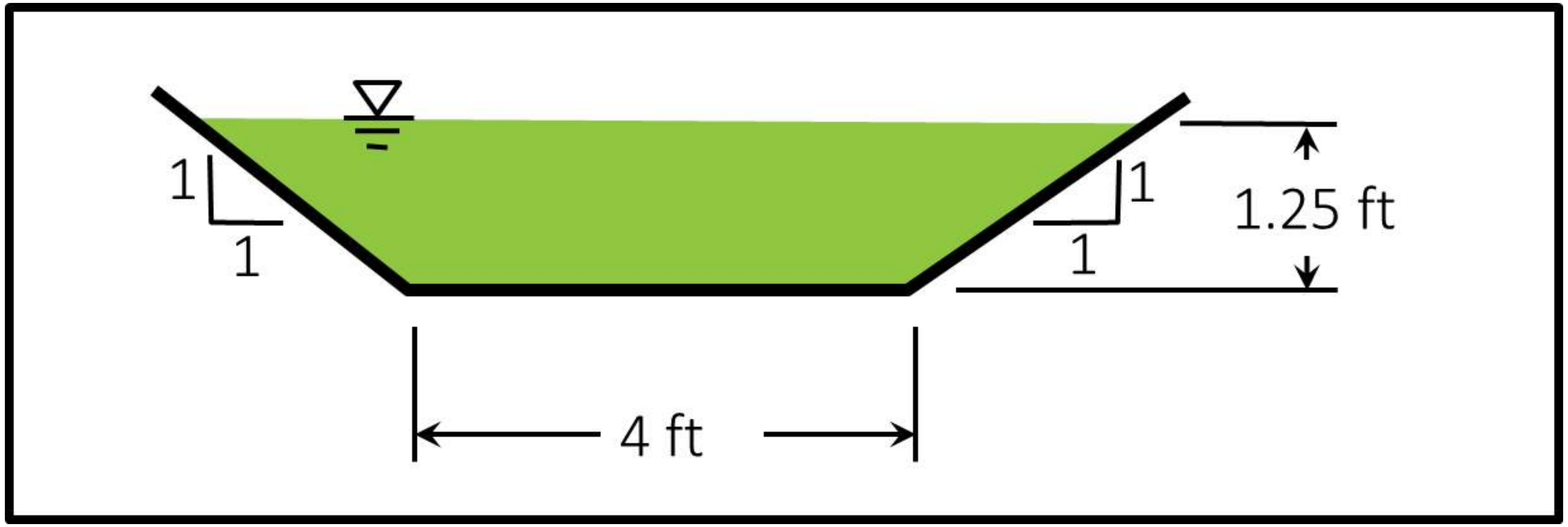
- Flow rate: $$q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}$$

$$q = \frac{1.49}{0.035}\left(7.81 \text{ ft}^2\right)\left(0.613 \text{ ft}\right)^{2/3}\left(0.0208 \text{ ft/ft}\right)^{1/2}$$

$$\boxed{q = 34.6 \text{ ft}^3\text{/s}}$$

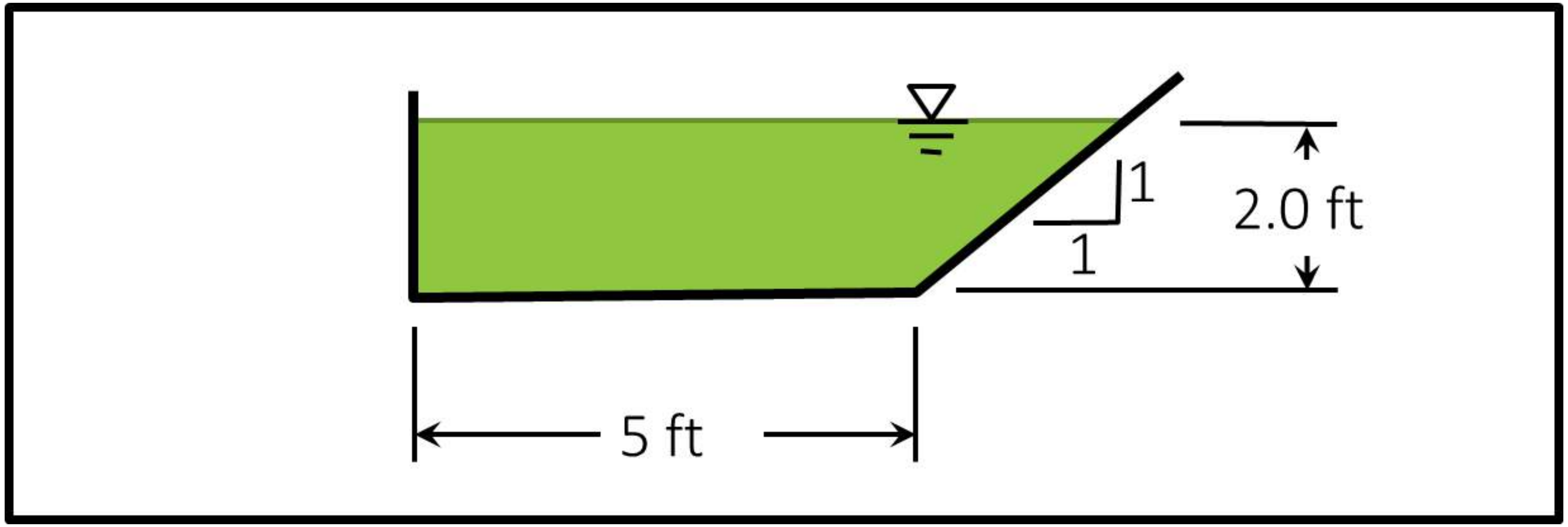
WORKSHOP PRACTICE 5:

- Compute the flow in a concrete lined channel (n = 0.015) having bottom width of 4 ft, side slopes of 1H:1V, flow depth of 1.25 ft, and bed slope of 0.00375 ft/ft.



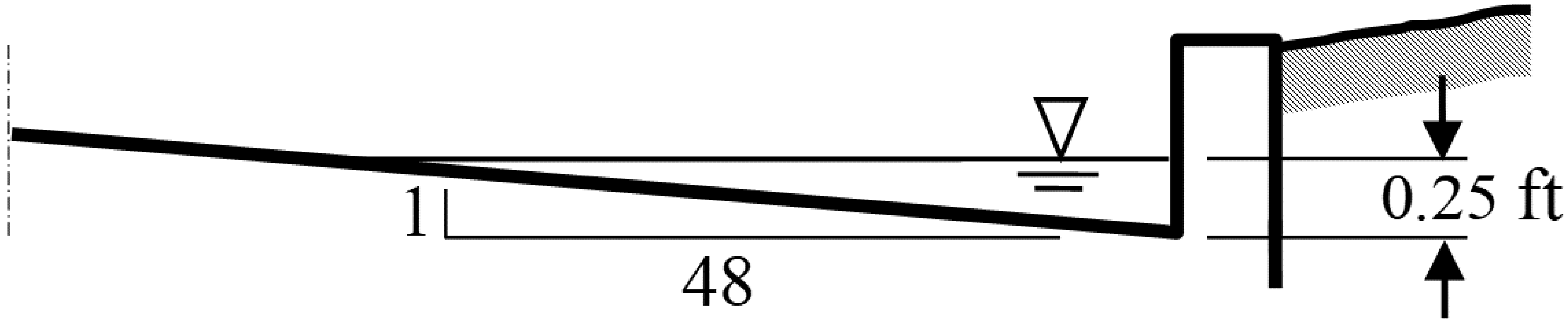
Workshop Practice 6:

- Compute the flow in a concrete lined channel (n = 0.015) having bottom width of 5 ft, vertical wall on the left side and side slope of 1H:1V on the right side, flow depth of 2.0 ft, and bed slope of 0.00682 ft/ft.



WORKSHOP PRACTICE 7:

- Determine the flow of a concrete street and curb gutter as shown in the figure. The flow-line slope is 0.0225 ft/ft.



Workshop Practice

- Practice 5

SS_{LEFT} =	1.0		S =	0.00375	ft/ft	y =	1.25	ft
SS_{RIGHT} =	1.0		n =	0.015				
B =	4.0	ft						

	Left	Center	Right	Total
A	0.781	5.000	0.781	6.563
P	1.768	4.000	1.768	7.536
R_h	-	-	-	0.871

q = 36.40 ft^3/s

- Practice 6

SS_{LEFT} =	0.0		S =	0.00682	ft/ft	y =	2.00	ft
SS_{RIGHT} =	1.0		n =	0.015				
B =	5.0	ft						

	Left	Center	Right	Total
A	0.000	10.000	2.000	12.000
P	2.000	5.000	2.828	9.828
R_h	-	-	-	1.221

q = 112.45 ft^3/s

- Practice 7

SS_{LEFT} =	48.0		S =	0.02250	ft/ft	y =	0.25	ft
SS_{RIGHT} =	0.0		n =	0.013				
B =	0.0	ft						

	Left	Center	Right	Total
A	1.500	0.000	0.000	1.500
P	12.003	0.000	0.250	12.253
R_h	-	-	-	0.122

q = 6.36 ft^3/s

Size a channel for runoff conveyance

- Flow capacity known
- Channel dimensions needed
- Manning's equation is applied

$$q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}$$

- Solve equation for dimension related parameters

$$\boxed{A R_h^{2/3} = \frac{q\,n}{1.49\, S^{1/2}}}$$

$AR_h^{2/3}$ is known as conveyance

- Typically, a trial-and-error solution

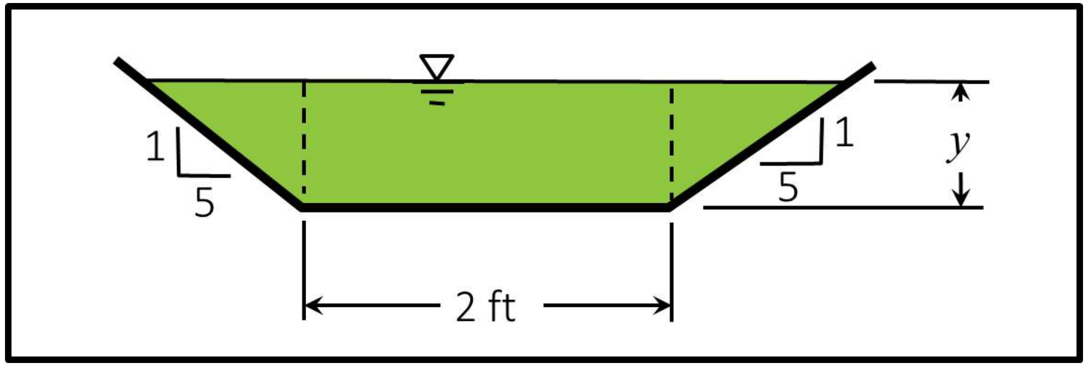
Example 4:

- Determine the section dimensions of a trapezoidal channel that must carry 24 ft^3/s on a bed slope of 0.0150 ft/ft, grass lining (n = 0.030), and maximum top width of 15 ft. The channel bottom must not be less than 2 ft, and the side slopes must not be steeper than 4 to 1.
  - Required conveyance is right side of : $A R_h^{2/3} = \dfrac{q\,n}{1.49\,S^{1/2}}$

$$\frac{q\,n}{1.49\,S^{1/2}} = \frac{\left(24\ \mathrm{ft}^3/\mathrm{s}\right)\left(0.030\right)}{1.49\left(0.015\ \mathrm{ft/ft}\right)^{1/2}} = 3.95$$

EXAMPLE 5:

- Select 5 to 1 side slopes, 2 ft wide bottom width to start. Express A and P in terms of flow depth y.



- Flow area: $A = (2)(y) + 2\left(\frac{1}{2}(y)(5y)\right) = 2y + 5y^2$

- Wetted perimeter: $P = 2 + 2\sqrt{(y)^2 + (5y)^2} = 2 + 2\sqrt{26y^2}$

Example 5: Continued…

- Trial 1: Try 1 ft flow depth to see if it will provide 3.95 conveyance. Check top width first (must be less than 15 ft)

$$T = 2\text{ ft} + 2(5)(1\text{ ft}) = 12\text{ ft}\quad\text{(OK)}$$

$$A = 2y + 5y^2 = (2\text{ ft})(1\text{ ft}) + 5(1\text{ ft})^2 = 7\text{ ft}^2$$

$$P = 2 + 2\sqrt{26y^2} = 2\text{ ft} + 2\sqrt{26(1\text{ ft})^2} = 12.20\text{ ft}$$

$$R_h = \frac{7}{12.20} = 0.574\text{ ft}$$

- Trial conveyance based upon trial dimensions is:

$$AR_h^{2/3} = (7)(0.574)^{2/3} = 4.83$$

Example 5: Continued…

- Compare required conveyance to trial conveyance:
  - Actual (4.83) is higher than required (3.95) so channel dimensions are adequate. However, a lower depth is possible.
- Trial 2: Try y = 0.70 ft

$$T = 2 + 2(5)(0.7) = 9.00 \text{ ft} \ \ (\text{OK})$$

$$A = 2(0.7) + 5(0.7)^2 = 3.85 \text{ ft}^2$$

$$P = 2 + 2\sqrt{26y^2} = 2 + 2\sqrt{26(0.7)^2} = 9.13 \text{ ft}$$

$$R_h = \frac{3.85}{9.13} = 0.421 \text{ ft}$$

$$AR_h^{2/3} = (3.84)(0.421)^{2/3} = 2.16$$

Example 5: Continued…

- Actual conveyance (2.16) is less than required (3.95) so actual depth is between 0.7 and 1.0 ft.
- Trial 3: Try y = 0.9 ft (top width still OK)

$$T = 2 + 2(5)(0.9) = 11.0 \text{ ft} \quad \text{(OK)}$$

$$A = 2(0.9) + 5(0.9)^2 = 5.85 \text{ ft}^2$$

$$P = 2 + 2\sqrt{26y^2} = 2 + 2\sqrt{26(0.9)^2} = 11.18 \text{ ft}$$

$$R_h = \frac{5.85}{11.18} = 0.523 \text{ ft}$$

$$AR_h^{2/3} = (5.85)(0.523)^{2/3} = 3.80 \text{ (low)}$$

Example 5:

- Actual (3.80) is short of the required (3.95) so need to increase depth. Try 0.92 ft with results in a summary table.

SS_{LEFT} =	5.0		S =	0.0150	ft/ft	q =	24.00	cfs
SS_{RIGHT} =	5.0		n =	0.030				
B =	2.0	ft						
		$qn/(1.49S^{1/2})$ =		3.95				

Trial	y	T	A	P	R	$AR^{2/3}$	Check	v
1	1.00	12.00	7.00	12.20	0.574	4.83	high	3.43
2	0.70	9.00	3.85	9.14	0.421	2.16	low	6.23
3	0.90	11.00	5.85	11.18	0.523	3.80	low	4.10
4	0.92	11.20	6.07	11.38	0.533	3.99	high	3.95

Example 5:

- Actual (3.99) is just above (3.95) so it is good!
  - Final Sizing: Grass lined trapezoidal channel
    - y = 0.92 ft
    - T = 11.2 ft
    - b = 2.0 ft
    - SS = 5:1 symmetrical
    - S = 0.015 ft/ft
    - v = 3.95 ft/s
- There are several other possible designs.

Example 6:

- Determine the section dimensions of a trapezoidal channel that must carry 45 ft^3/s on a bed slope of 0.0107 ft/ft, grass lining, and maximum top width of 25 ft. The channel bottom must not be less than 4 ft, and the side slopes must not be steeper than 3 to 1.

- Final Possible Designs:

No.	y (ft)	T (ft)	b (ft)	SS	S (ft/ft)	v (ft/s)
1	1.4	14.9	4	3	0.0107	3.92
2	1.3	14.4	4	4	0.0107	3.76
3	1.3	12.8	5	3	0.0107	3.89
4	1.2	15.6	6	4	0.0107	3.47

Manning's Equation for Pipe Sizing

SIZING A PIPE FOR RUNOFF CONVEYANCE

- Pipes flowing partially full are circular open channels.
- Manning's equation is applied.

$$\boxed{q = \frac{1.49}{n} A R_h^{2/3} S^{1/2}}$$

- Preliminary sizing assumes full-barrel gravity flow.
- Pipe selection automatically creates a design with pipe flowing partially full (desired result)

SIZING A PIPE FOR RUNOFF CONVEYANCE

- Hydraulic radius can be simplified for a pipe flowing full....

$$A = \frac{\pi D^2}{4} \qquad P = \pi D$$

$$R_h = \frac{\pi D^2}{4} \times \frac{1}{\pi D} = \frac{D}{4}$$

Sizing a pipe for runoff conveyance

- Algebraic substitution of A and Rh into Manning's…

$$q = \frac{1.49}{n}\frac{\pi D^2}{4}\left(\frac{D}{4}\right)^{2/3} S^{1/2}$$

$$\boxed{q = \frac{0.46}{n} D^{8/3} S^{1/2}}$$

Sizing a Pipe for Runoff Conveyance

- Algebraic manipulation, solve for D…

$$D(\text{feet}) = 1.33\left(\frac{q\,n}{S^{1/2}}\right)^{3/8}$$

$$\boxed{D(\text{inches}) = 16\left(\frac{q\,n}{S^{1/2}}\right)^{3/8}}$$

EXAMPLE 7:

- Determine the pipe size necessary to carry 17.5 ft^3/sec of flow if the pipe material is smooth reinforced concrete and pipe slope is 0.0185 ft/ft.
  - Roughness for concrete pipe: 0.013
  - Minimum diameter:

$$D_{\min} = 16\left(\frac{q\,n}{S^{1/2}}\right)^{3/8} = 16\left(\frac{17.5\times 0.013}{0.0185^{1/2}}\right)^{3/8}$$

$$D_{\min} = 19.40 \text{ inches}$$

  - Manufactured diameters: 18, 24, 30, etc.

Use 24" diameter concrete pipe at 1.85%

EXAMPLE 8:

- Determine the pipe size necessary to carry 21.8 ft^3/s of flow if the pipe material is corrugated metal and pipe slope is 0.0220 ft/ft.
  - Roughness for CMP: 0.024 (typical)
  - Minimum diameter:

$$D_{min} = 16\left(\frac{q\,n}{S^{1/2}}\right)^{3/8} = 16\left(\frac{21.8 \times 0.024}{0.0220^{1/2}}\right)^{3/8}$$

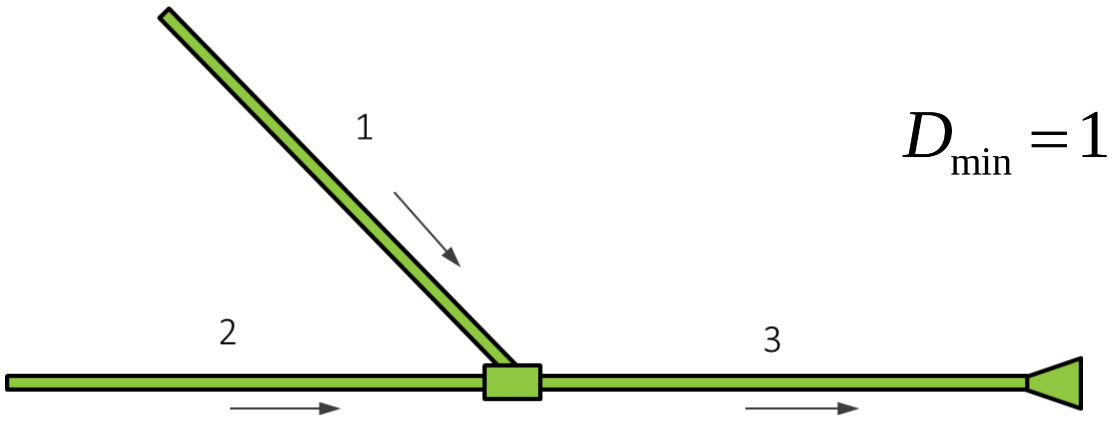
$$D_{min} = 25.7 \text{ inches}$$

Use 30" diameter CMP (n=0.024) at 2.20%

Workshop Practice 8:

Pennoni

- Given a three-pipe network with q, n, S
- Determine pipe diameters for each pipe

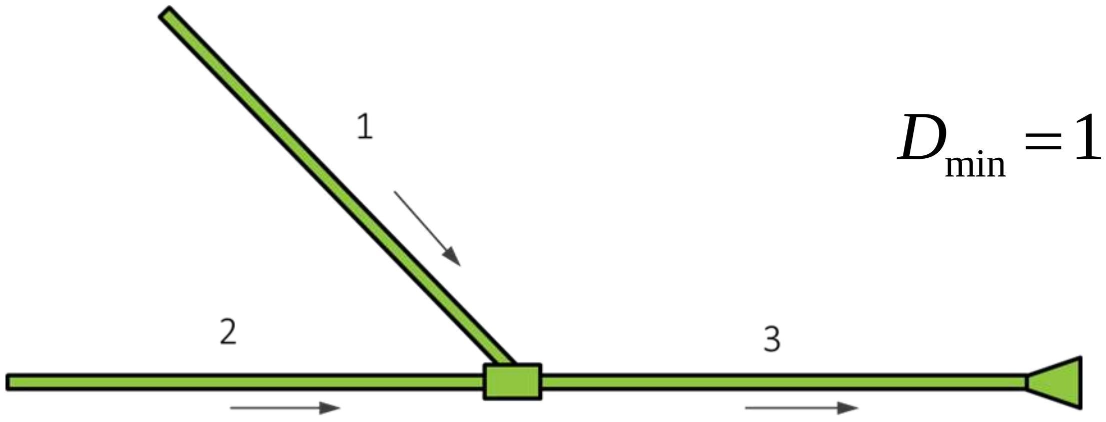


$$D_{min} = 16\left(\frac{q\,n}{S^{1/2}}\right)^{3/8}$$

Pipe	q (ft^3/s)	n	S (ft/ft)	D_{min} (in)	D (in)
1	17	0.011	0.0375		
2	33	0.024	0.0282		
3	50	0.013	0.0143		

Workshop Practice 8 Answers:

- Given a three-pipe network with q, n, S
- Determine pipe diameters for each pipe

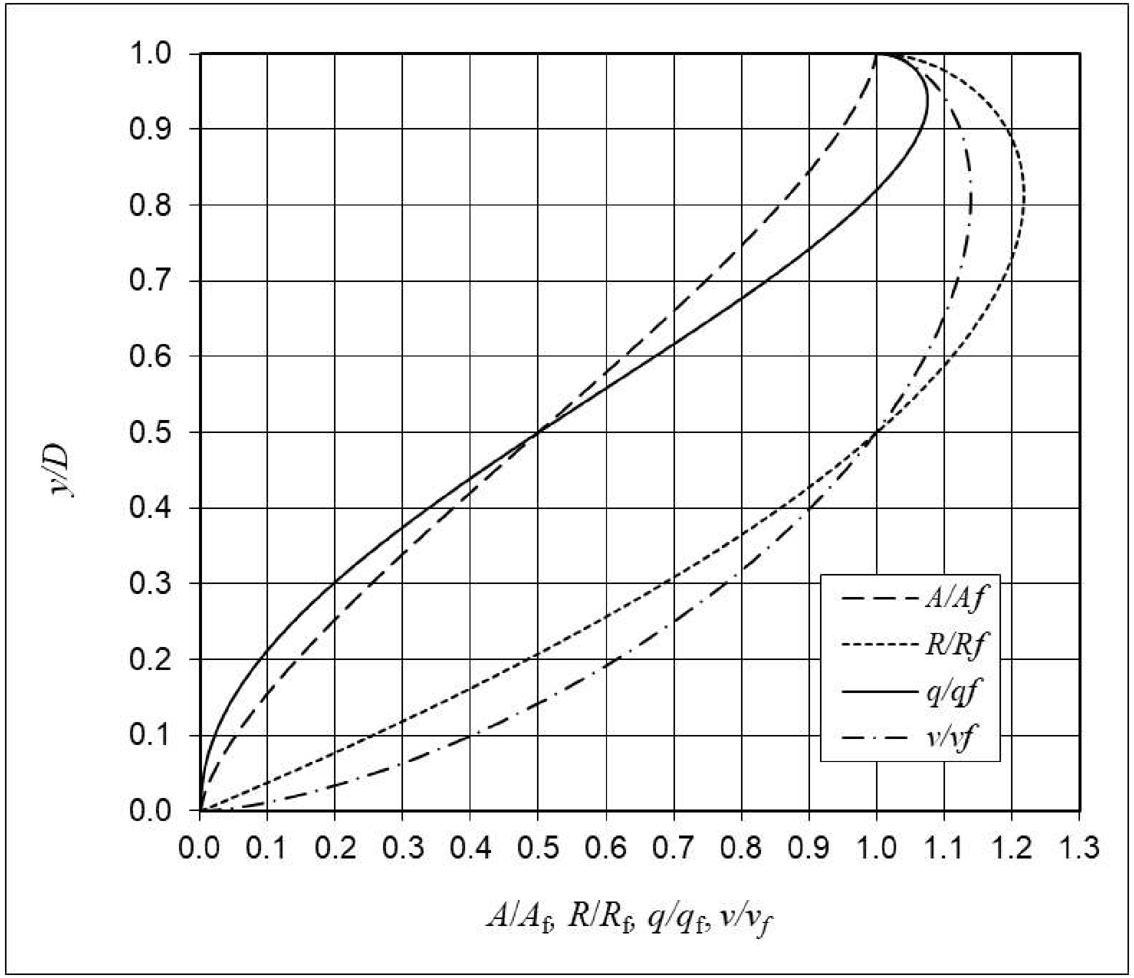


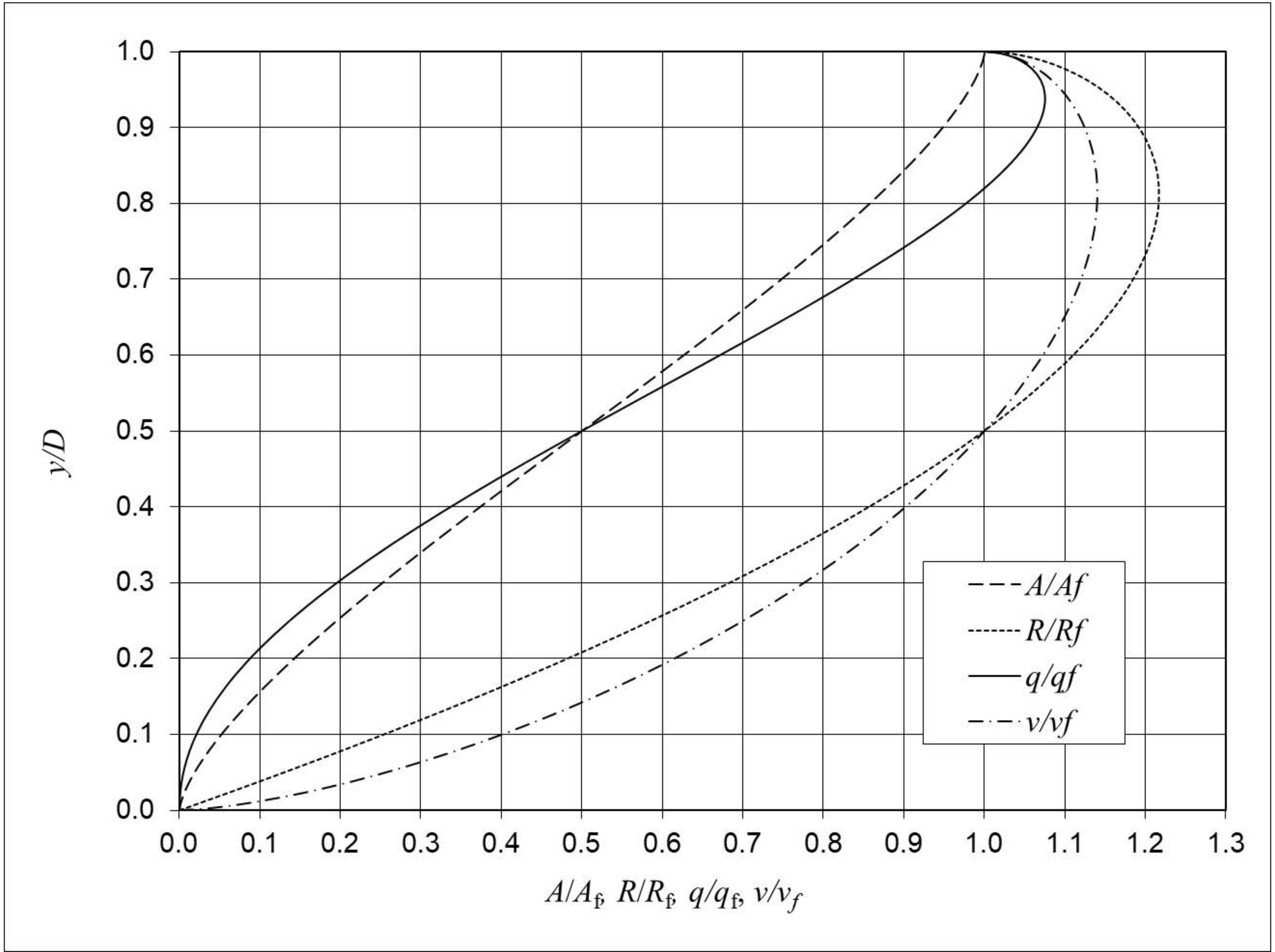
$$D_{\min} = 16\left(\frac{q\,n}{S^{1/2}}\right)^{3/8}$$

Pipe	q (ft^3/s)	n	S (ft/ft)	D_{min} (in)	D (in)
1	17	0.011	0.0375	15.79	18
2	33	0.024	0.0282	28.6	30
3	50	0.013	0.0143	30.2	36

Hydraulic elements chart for circular pipes

- A tool used to evaluate partial depth flow in circular pipes
- Works on parameters of flow, flow area, flow depth, hydraulic radius and velocity
- Use illustrated by example





1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
y/D
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3
A/Af, R/Rf, q/qf, v/vf
A/Af
R/Rf
q/qf
v/vf

Example 9:

- For the pipe sized in Example 7, determine the full flow capacity of the pipe and the design flow depth, y.
  - Design flow: 17.5 ft^3/s
  - Design slope: 0.0185 ft/ft
  - Design diameter: 24" (2 ft)
  - Roughness for concrete pipe: 0.013
  - Compute pipe full flow capacity using Manning's from slide 77 …

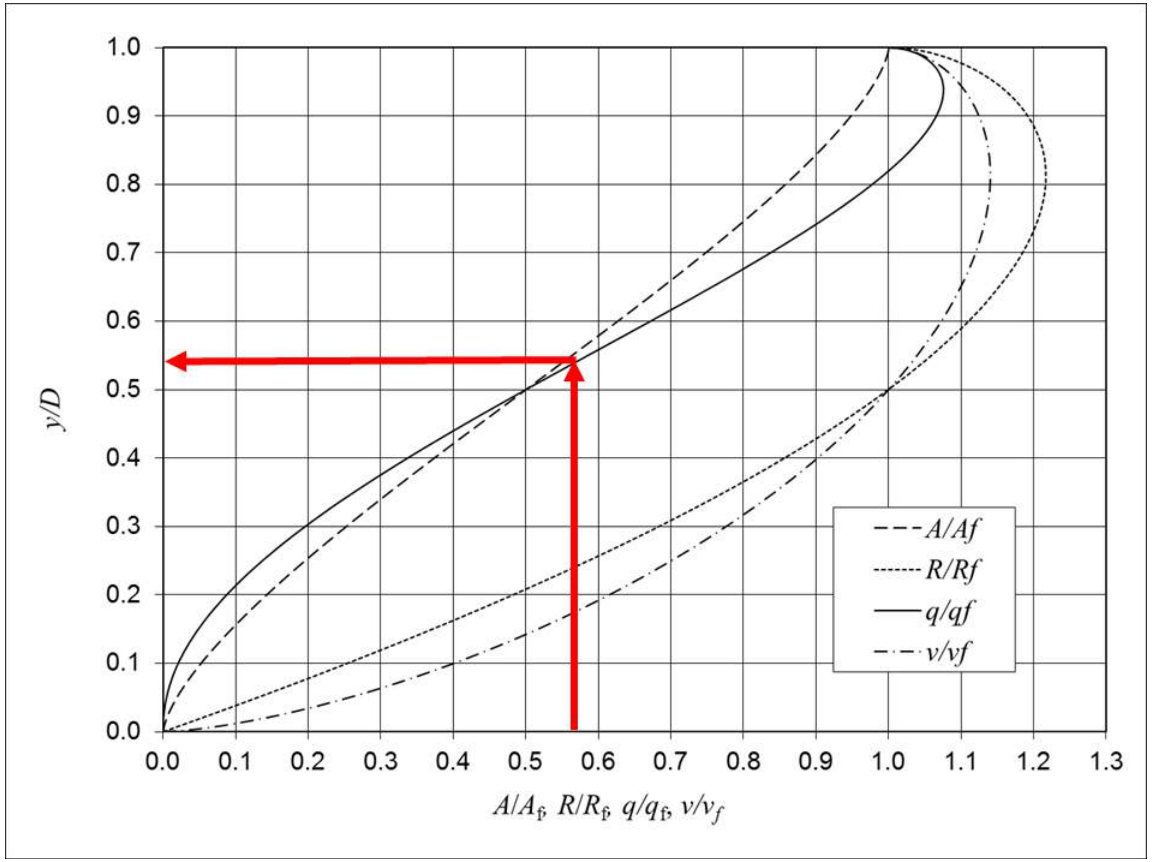
$$q_{\text{full}} = \frac{0.46}{n} D^{8/3} S^{1/2} = \frac{0.46}{0.013}(2.0\text{ ft})^{8/3}(0.0185\text{ ft/ft})^{1/2}$$

$$\boxed{q_{\text{full}} = 30.6\text{ ft}^3/\text{s}}$$

EXAMPLE 9: CONTINUED...

- Compute the ratio qdesign to qfull :

$$\frac{q_{\text{design}}}{q_{\text{full}}} = \frac{17.5}{30.6\ \text{ft}^3/\text{s}} = 0.57$$



From chart read:
y/D = 0.53

Thus:

$$y = 0.53(24\ \text{in})$$

$$\boxed{y = 12.72\ \text{in}}$$

Example 10:

- For the pipe sized in Example 8, determine the full flow capacity of the pipe qf, the design flow depth y and the design velocity, v.
  - Design flow: 21.8 ft^3/s
  - Design slope: 0.0220 ft/ft
  - Design diameter: 30” (2.5 ft)
  - Roughness for corrugated metal pipe: 0.024
  - Compute pipe full flow using Manning’s from slide 78 …

$$q_f = \frac{0.46}{n} D^{8/3} S^{1/2} = \frac{0.46}{0.024} (2.5\text{ ft})^{8/3} (0.0220\text{ ft/ft})^{1/2}$$

$$\boxed{q_f = 32.7\text{ ft}^3/\text{s}}$$

Example 10: continued...

- Compute pipe full velocity...

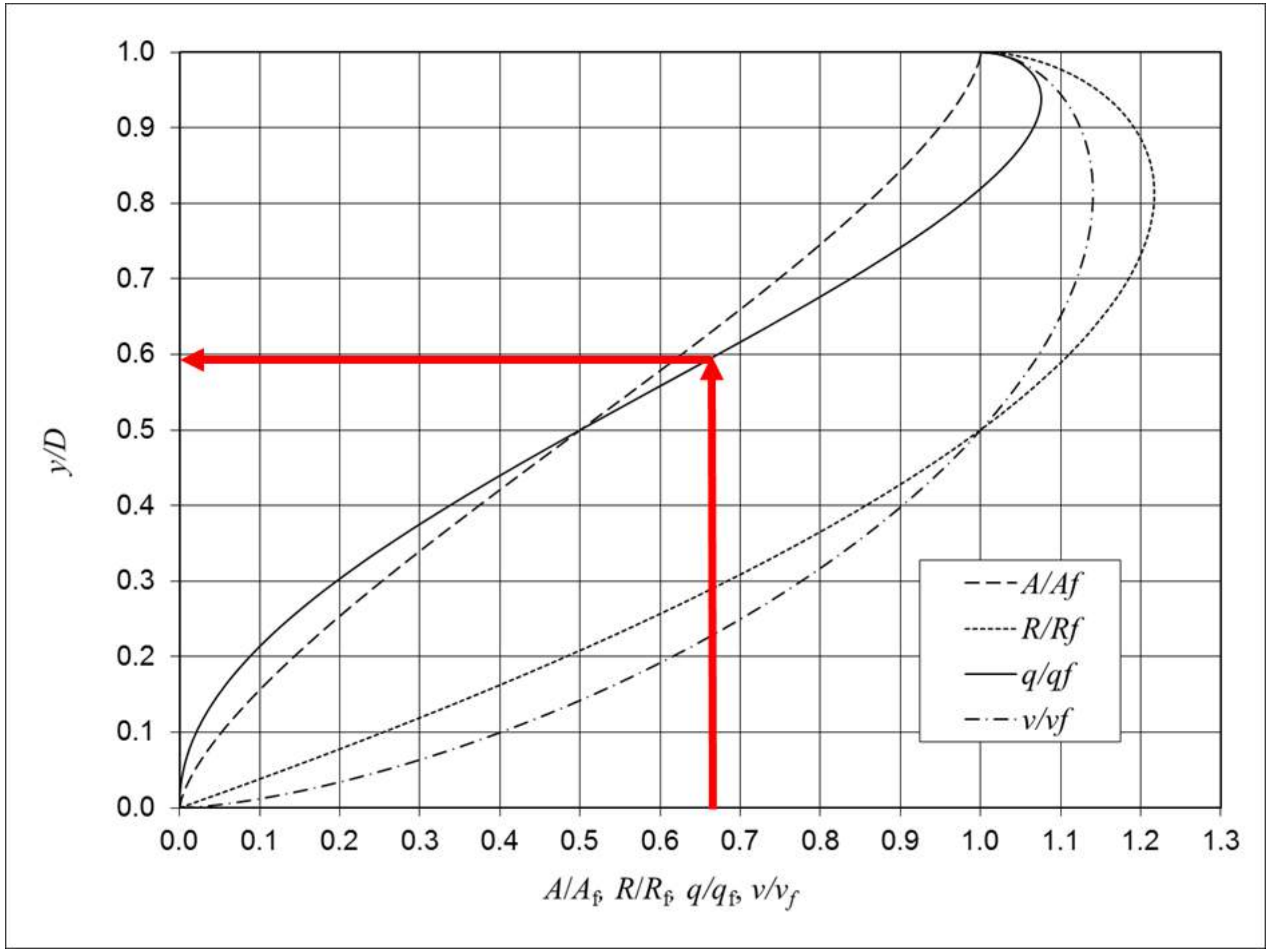
$$A_{\mathrm{f}} = \frac{\pi D^2}{4} = \frac{\pi \left(2.5\right)^2}{4} = 4.91\ \mathrm{ft}^2$$

$$v_{\mathrm{f}} = \frac{q_{\mathrm{f}}}{A_{\mathrm{f}}} = \frac{32.7\ \mathrm{ft}^3/\mathrm{s}}{4.91\ \mathrm{ft}^2} = 6.66\ \mathrm{ft/s}$$

EXAMPLE 10: CONTINUED...

- Compute the ratio q to qf :

$$\frac{q}{q_f} = \frac{21.8}{32.7\ \text{ft}^3/\text{s}} = 0.67$$



From chart read:
y/D = 0.59

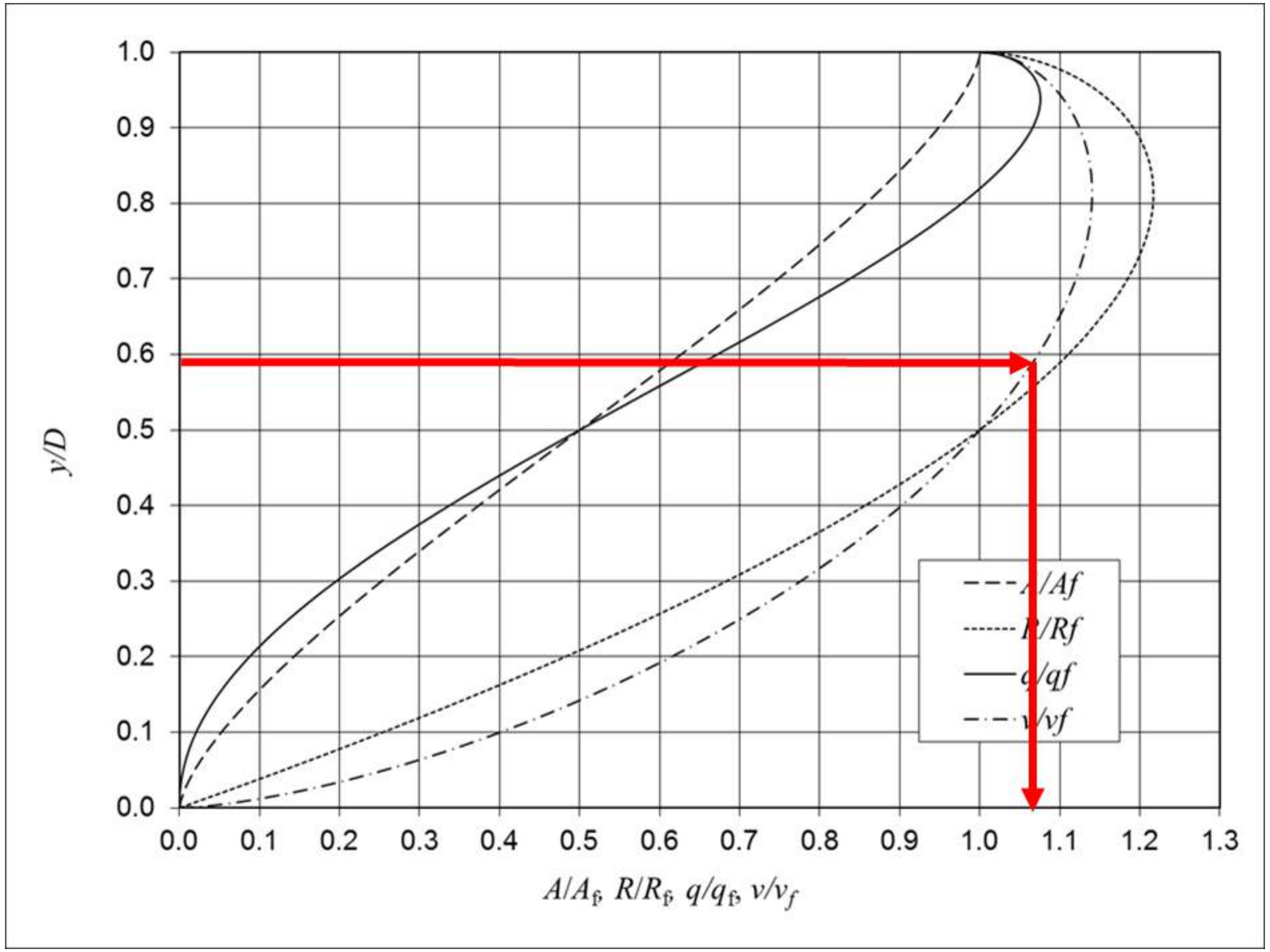
Thus:

$$y = 0.59(30\ \text{in})$$

$$\boxed{y = 17.7\ \text{in}}$$

EXAMPLE 10: CONTINUED...

- From the chart with y/d = 0.59 read the ratio of v/vf = 1.07



$$\frac{v}{v_f} = 1.07$$

Thus:

$$v = 1.07\, v_f$$

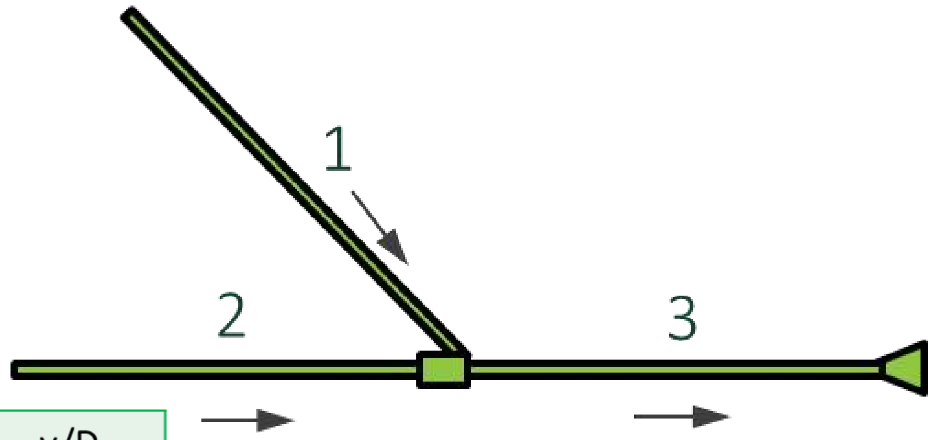
$$v = 1.07\left(6.66 \text{ ft/s}\right)$$

$$\boxed{v = 7.13 \text{ ft/s}}$$

WORKSHOP PRACTICE 9:

- Given a three-pipe network with q, n, S and D
  Determine qf, y and v

$$q_f = \frac{0.46}{n} D^{8/3} S^{1/2} \quad A_f = \frac{\pi D^2}{4} \quad v = \frac{q}{A}$$



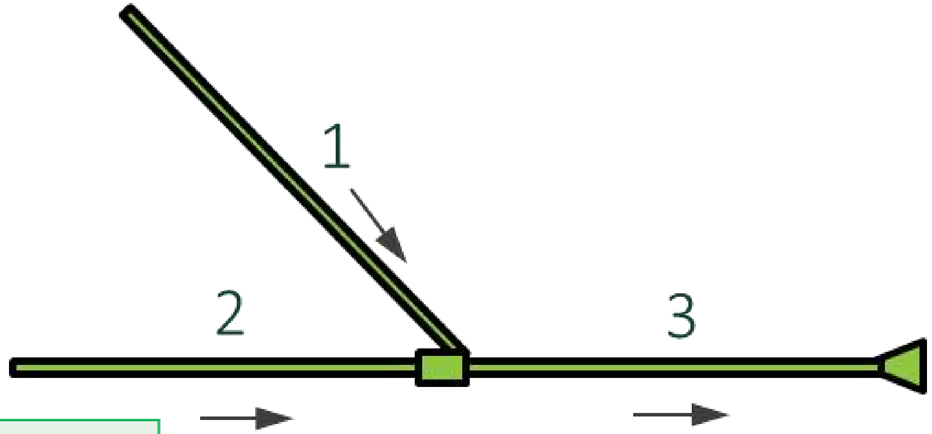
Pipe	q (ft^3/s)	n	S (ft/ft)	D (ft)	q_f (ft^3/s)	q/q_f	y/D
1	17	0.011	0.0375	1.5			
2	33	0.024	0.0282	2.5			
3	50	0.013	0.0143	3.0			

Pipe	y (ft)	v/v_f	A_f (ft^2)	v_f (ft/s)	v (ft/s)
1					
2					
3					

Workshop Practice 9: Answers

- Given a three-pipe network with q, n, S and D
  Determine qf, y and v

$$q_f = \frac{0.46}{n} D^{8/3} S^{1/2} \qquad A_f = \frac{\pi D^2}{4} \qquad v = \frac{q}{A}$$



Pipe	q (ft^3/s)	n	S (ft/ft)	D (ft)	q_f (ft^3/s)	q/q_f	y/D
1	17	0.011	0.0375	1.5	23.9	0.71	0.62
2	33	0.024	0.0282	2.5	37.0	0.89	0.74
3	50	0.013	0.0143	3.0	79.2	0.63	0.58

Pipe	y (ft)	v/v_f	A_f (ft^2)	v_f (ft/s)	v (ft/s)
1	0.93	1.09	1.77	13.5	14.7
2	1.85	1.13	4.91	7.53	8.50
3	1.74	1.07	7.07	11.2	12.0

CONVEYANCE WORKSHOP SUMMARY

Pennoni

- Topics
  - Rational formula for peak runoff flows
  - Manning's equation for pipe sizing
  - Manning's Equation for swale design for overland flow

- Outcomes
  - Estimate peak flow rates using the Rational Equation
  - Size a channel using Manning's Equation
  - Use Manning's equation to analyze and size channels and pipes flowing partially full
  - Use the hydraulic elements chart for circular pipes to determine flow area, depth and velocity design conditions