DAY 2 Work Problems

- Outlet Protection
- Open Channel Flow
- Manning’s Equation
- Time of Concentration
- Rational Formula
- Graphic Peak Design Method (TR55)

OUTLET PROTECTION CALCULATIONS ESCH III-154-165

1. **Given a discharge of 20 cfs from a 15 inch pipe into water depth less than half the pipe diameter (Minimum Tailwater Condition), what is the apron length, La (feet); median stone size of riprap, d(50); upstream apron width, Wu (feet); and downstream apron width, Wd (feet), required for outlet protection?**

From ESCH III-164, Plate 3.18-3 (Minimum Tailwater Condition)

On the bottom horizontal axis, select the given Discharge, Q = ( ) cfs

Read up to bottom chart to given Pipe Diameter, D = ( ) inches

Read over to right for median size riprap stone, d(50) = ( ) feet

From Discharge, Q = ( ) cfs, read up to top chart to Pipe Diameter, D = ( ) inches

Read to left for Minimum Apron Length, La = ( ) feet

$$Wu = 3 \times D$$

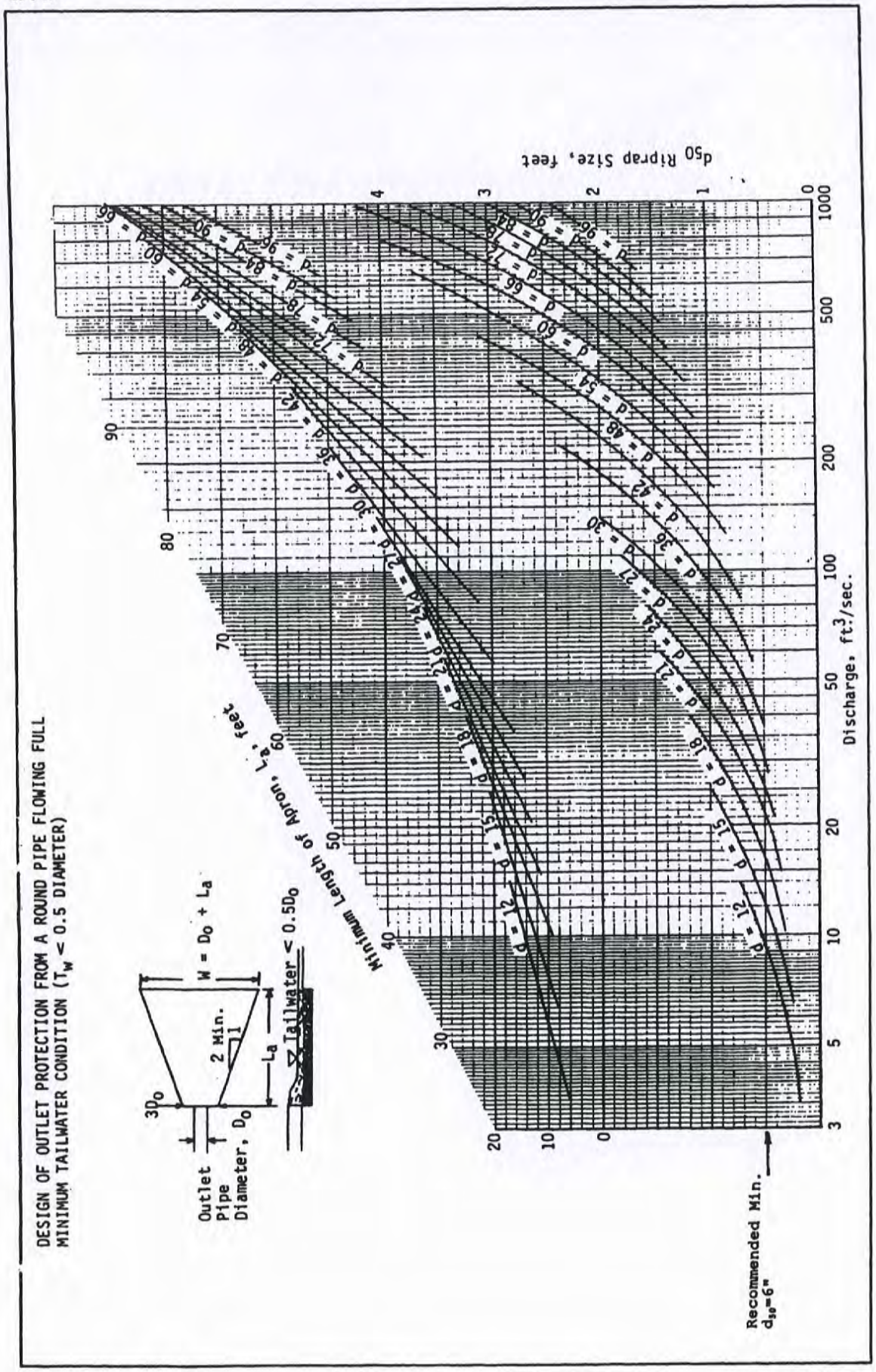
Wu (Upstream Apron Width, feet) = 3 x D (Pipe Diameter, feet)

Wu = 3 x ( ) feet = ( ) feet

$$Wd = D + La$$

Wd (Downstream Apron Width, feet) = D (Pipe Diameter feet) + La (Apron Length feet)

Wd = ( ) feet + ( ) feet = ( ) feet



Source: USDA-SCS

Plate 3.18-3

2. From a 24 inch pipe flows 50 cfs into water depth greater than half the pipe diameter (Maximum Tailwater Condition), what is the apron length, LA (feet); median stone size, d(50); upstream apron width, Wu (feet); and downstream apron width, Wd (feet), required for outlet protection?

From ESCH III-165, Plate 3.18-4 diameter (Maximum Tailwater Condition)

On the bottom horizontal axis, select the given Discharge, Q = ( ) cfs

Read up to bottom chart to given Pipe Diameter, D = ( ) inches

Read over to right for median size riprap stone, d(50) = ( ) feet

From Discharge, Q = ( )cfs, read up to top of chart to Pipe Diameter, D = ( )inches

Read to left for Minimum Apron Length, La = ( ) feet

$$Wu = 3 \times D$$

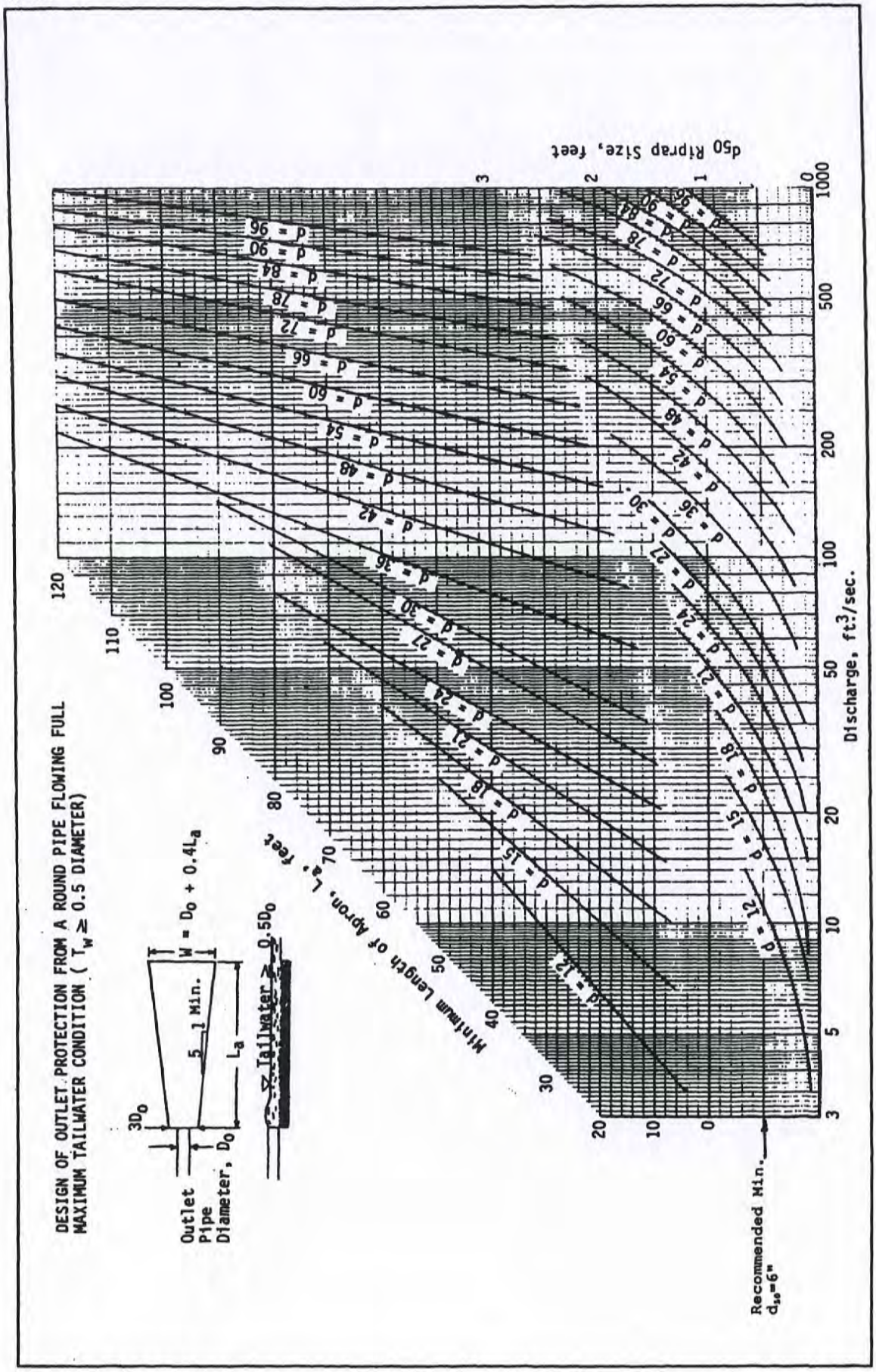
Wu (Upstream Apron Width, feet) = 3 x D (Pipe Diameter, feet)

Wu = 3 x ( ) feet = ( ) feet

$$Wd = D + 0.4 \times La$$

Wd (Downstream Apron Width, feet) = D (Pipe Diameter, feet) + 0.4 x La (Apron Length, feet)

Wd = ( ) feet + 0.4 x ( ) feet = ( ) feet



Source: USDA-SCS

Plate 3.18-4

OPEN CHANNEL FLOW ESCH V-96 to 141

1. **What is the cross-sectional area (a) of a rectangular channel with a bottom (b) width of 4 feet and a depth (d) of 2 feet?**

$$a = b \times d$$

A (Rectangular Channel Area, square feet) = b (Bottom Width, feet) x d (Depth, feet)

a = ( ) feet x ( ) feet = ( ) square feet

2. **For this same channel, what is the Wetted Perimeter, p (feet)?**

$$p = b + 2d$$

P (Wetted Perimeter, feet) = b (Bottom width, feet) + 2 x d (Depth, feet)

p = ( ) feet + 2( ) feet = ( ) feet

3. **For this same channel, what is the Hydraulic Radius, r (feet)?**

$$r = \frac{a}{p}$$

r (Hydraulic Radius, feet) = a (Area, square feet) / p (Wetted Perimeter, feet)

r = ( ) square feet / ( ) feet = ( ) feet

4. **For a 3 feet deep triangular channel with side slopes of 3 feet horizontal to 1 foot vertical (3:1), what is the cross-sectional area?**

For Triangular Channel Area:

$$a = z \times d^2$$

Where:

d = channel depth (feet)

z = channel side slopes of Horizontal Distance [z = ( ) to vertical distance = 1]

a = ( ) x [( ) feet]^2 = ( ) square feet

5. For this same channel, what is the Wetted Perimeter, p (feet)?

$$p = 2 \times d\sqrt{\left(z^2 + 1\right)}$$

or

$$p = 2 \times d(z^2 + 1)^{\frac{1}{2}}$$

Where:

p= Wetted Perimeter (feet)

d = channel depth (feet)

z = channel side slopes of Horizontal Distance [z = ( ) to vertical distance = 1]

p = 2 x ( ) x [( )^2 + 1]$^{1/2}$ = ( ) feet

6. For this same channel, what is the Hydraulic Radius?

$$r = \frac{a}{p}$$

r (Hydraulic Radius, feet) = a (Area, square feet) / p (Wetted Perimeter, feet)

r = ( ) square feet / ( ) feet = ( ) feet

7. For a trapezoidal channel 3 feet deep, bottom width of 6 feet and 4:1 side slopes, what is the cross-sectional area (a)?

For trapezoidal area:

$$a = \left(b \times d\right) + \left(z \times d^2\right)$$

Where:

b= bottom width (feet)

d = channel depth (feet)

z = channel side slopes of Horizontal Distance [z = ( ) to vertical distance = 1]

a = [( ) feet x ( ) feet] + [( ) x {( ) feet}^{2}] = ( ) square feet

8. For this same channel, what is the Wetted Perimeter, p (feet)?

$$p = b + 2d\sqrt{\left(z^2 + 1\right)}$$

or

$$p = b + 2d\left(z^2 + 1\right)^{\frac{1}{2}}$$

p = ( ) feet + 2 x ( ) feet x [( )^2 + 1]$^{1/2}$ = ( ) feet

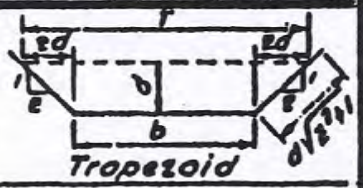
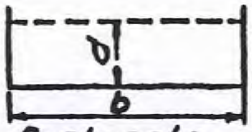
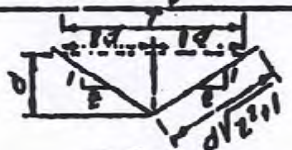
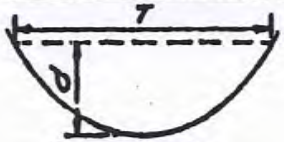
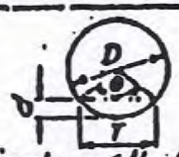
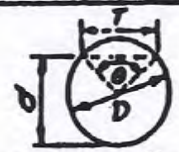
9. For this same channel, what is the Hydraulic Radius, r(feet)?

$$r = \frac{a}{p}$$

r (Hydraulic Radius, feet) = a (Area, square feet) / p (Wetted Perimeter, feet)

r = ( ) square feet / ( ) feet = ( ) feet

ble 5.2 Equations for Channel Cross-Sections[8]

Section	Area a	Wetted Perimeter p	Hydraulic Radius r	Top Width T
 Trapezoid	$bd+zd^2$	$b+2d\sqrt{z^2+1}$	$\frac{bd+zd^2}{b+2d\sqrt{z^2+1}}$	$b+2zd$
 Rectangle	bd	$b+2d$	$\frac{bd}{b+2d}$	b
 Triangle	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$
 Parabola	$\frac{2}{3}dT$	$T+\frac{8d^2}{3T}$ [1]	$\frac{2dT^2}{3T^2+8d^2}$ [1]	$\frac{3a}{2d}$
 Circle - <½ full [2]	$\frac{D^2}{8}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$\frac{\pi D\theta}{360}$	$\frac{45D}{\pi\theta}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$
 Circle - >½ full [3]	$\frac{D^2}{8}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$\frac{\pi D(360-\theta)}{360}$	$\frac{45D}{\pi(360-\theta)}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$

[1] Satisfactory approximation for the interval $0<\frac{d}{T}\leq 0.25$
When $d/T>0.25$, use $p=\frac{1}{2}\sqrt{16d^2+T^2}+\frac{T^2}{8d}\sinh^{-1}\frac{4d}{T}$

[2] $\theta=4\sin^{-1}\sqrt{d/D}$
[3] $\theta=4\cos^{-1}\sqrt{d/D}$
Insert θ in degrees in above equations

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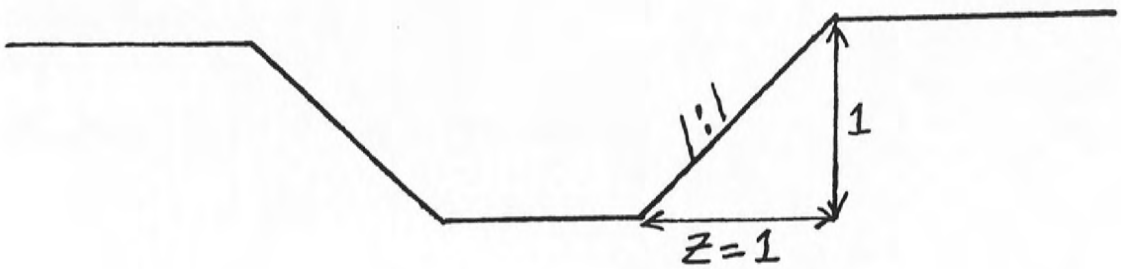
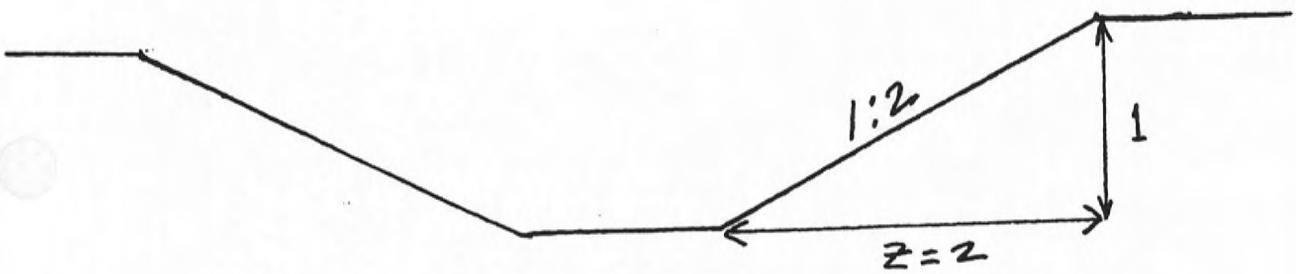
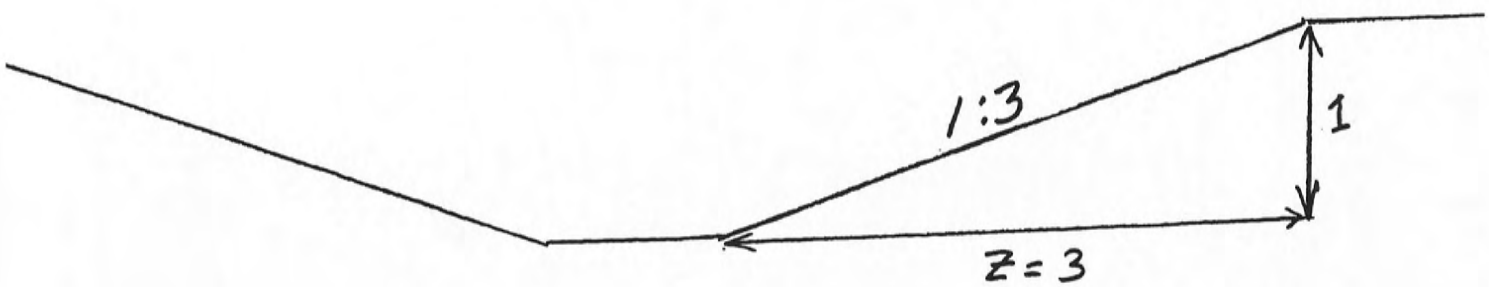
Open Channel Flow – Side Slopes

Rise/Run = Vertical Change/Horizontal Change = 1/z







Manning's Roughness Coefficients, n
Training Notebook for Plan Reviewers, Table 5.1, Page V-5
ESCH V-61, 62, 63

10. What is the range of Manning's Roughness Coefficient for concrete pipe?

n = ( ) to ( )

11. What is the range of Manning's Roughness Coefficient for a winding natural stream channel with some pools and shoals, some weeds and stones?

n = ( ) to ( )

12. Given a concrete lined triangular channel, with Manning's Roughness Coefficient, n = 0.015; Slope, S = 0.02 feet/foot slope; and Hydraulic Radius, R = 1.4, what is the velocity of flow in this channel?

Manning's Equation

$$V = \frac{1.49}{n} \times \sqrt[3]{R^2} \times \sqrt{S}$$

or

$$V = \frac{1.49}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

Where:

V = Velocity (fps)

n = Manning's Roughness Coefficient

R = Hydraulic Radius (feet)

S = Slope of the Channel (feet/foot)

V = [1.49 / ( )] x ( )$^{2/3}$ x ( )$^{1/2}$ = ( ) fps

13. For a Bermuda grass lined channel, with a Manning's Roughness Coefficient, n = 0.05, Slope, S = 0.06 feet/foot, and Hydraulic Radius, R = 1.5, what is the velocity of flow in this channel and does it exceed the permissible velocity for Bermuda grass?

$$V = \frac{1.49}{n} \times \sqrt[3]{R^2} \times \sqrt{S}$$

or

$$V = \frac{1.49}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

Where:

V = Velocity (fps)

n = Manning's Roughness Coefficient

R = Hydraulic Radius (feet)

S = Slope of the Channel (feet/foot)

V = [1.49 / ( )] x ( )$^{2/3}$ x ( )$^{1/2}$ = ( ) fps

From ESCH V-120, Table 5-14, Permissible Velocities for Grass-Lined Channels

$$S = s \times 100$$

Where:

S = Channel Slope (%)

s = Channel Slope (feet/foot)

S(%) = ( ) feet/foot x 100 = ( )%

Permitted Velocity for Bermuda Grass at Slope ( )% = ( )fps

14. What is the flow rate of a channel with a velocity (V) of 4 feet/second and a cross-sectional area (A) of 50 square feet?

Continuity Equation:

$$Q = V \times A$$

Where:

V = Velocity (feet/second)

A = Area (square feet)

Q = ( ) feet/second x ( ) quare feet = ( ) cubic feet/second

TABLE 5-7
ROUGHNESS COEFFICIENTS
(MANNING'S "n") FOR SHEET FLOW

Surface Description	n[1]
Smooth surfaces (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[2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods[3]:	
Light underbrush	0.40
Dense underbrush	0.80

[1] The "n" values are a composite of information compiled by Engman (1986).

[2] Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

[3] When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Source: USDA-SCS

TABLE 5-8

MANNING'S "n" VALUES

Surface	Best	Good	Fair	Bad
Uncoated cast-iron pipe	0.012	0.013	0.014	0.015
Coated cast-iron pipe	0.011	0.012*	0.013*	
Commercial wrought-iron pipe, black	0.012	0.013	0.014	0.015
Commercial wrought-iron pipe, galvanized	0.013	0.014	0.015	0.017
Riveted and spiral steel pipe	0.013	0.015*	0.017*	
Common clay drainage tile	0.011	0.012*	0.014*	0.017
Neat cement surfaces	0.010	0.011	0.012	0.013
Cement mortar surfaces	0.011	0.012	0.013*	0.015
Concrete pipe	0.012	0.013	0.015*	0.016
Concrete-lined channels	0.012	0.014*	0.016*	0.018
Cement-rubble surface	0.017	0.020	0.025	0.030
Dry-rubble surface	0.025	0.030	0.033	0.035
Canals and ditches:				
Earth, straight and uniform	0.017	0.020	0.0225*	0.025
Rock cuts, smooth and uniform	0.025	0.030	0.033	0.035
Rock cuts, jagged and irregular	0.035	0.040	0.045	
Winding sluggish canals	0.0225	0.025*	0.0275	0.030
Dredged earth channels	0.025	0.0275*	0.030	0.033
Canals with rough stony beds, weeds on earth banks	0.025	0.030	0.035*	0.040
Earth bottom, rubble sides	0.028	0.030*	0.033*	0.035

* Values commonly used in designing.

Source: King

TABLE 5-8 (continued)

MANNING'S "n" VALUES

Surface	Best	Good	Fair	Bad
Natural Stream Channels:				
1. Clean, straight bank, full stage, no rifts or deep pools	0.025	0.0275	0.030	0.033
2. Same as #1, but some weeds and stones	0.030	0.033	0.035	0.040
3. Winding, some pools and shoals, clean	0.033	0.035	0.040	0.045
4. Same as #3, lower stages, more ineffective slope and sections	0.040	0.045	0.050	0.055
5. Same as #3, some weeds and stones	0.035	0.040	0.045	0.050
6. Same as #4, stony sections	0.045	0.050	0.055	0.060
7. Sluggish river reaches, rather weedy or with very deep pools	0.050	0.060	0.070	0.080
8. Very weedy reaches	0.075	0.100	0.125	0.150

* Values commonly used in designing.

Source: King

TABLE 5-12

MANNING "n" VALUES FOR SELECTED CHANNEL LINING MATERIALS

Material	Range of "n" Values
Concrete	
- Formed	0.013 - 0.017
- Trowel Finish	0.012 - 0.014
- Float Finish	0.013 - 0.015
- Gunite	0.016 - 0.022
Gravel Bed, Formed Concrete Sides	0.017 - 0.020
Asphalt Concrete	
- Smooth	0.013
- Rough	0.016
Corrugated Metal	
- 2-2/3" x 1/2" Corrugations	0.024
- 6" x 2" Corrugations	0.032
Concrete Pipe	0.011 - 0.013

Source: Va. DSWC

TABLE 5-14

PERMISSIBLE VELOCITIES FOR GRASS-LINED CHANNELS

Channel Slope	Lining	Velocity* (ft./sec.)
0 - 5%	Bermudagrass	6
	Reed canarygrass Tall fescue Kentucky bluegrass	5
	Grass-legume mixture	4
	Red fescue Redtop Sericea lespedeza Annual lespedeza Small grains Temporary vegetation	2.5
5 - 10%	Bermudagrass	5
	Reed canarygrass Tall fescue Kentucky bluegrass	4
	Grass-legume mixture	3
Greater than 10%	Bermudagrass	4
	Reed canarygrass Tall fescue Kentucky bluegrass	3

* For highly erodible soils, decrease permissible velocities by 25%.

Source: Soil and Water Conservation Engineering, Schwab, et. al. and American Society of Civil Engineers.

Manning's Equation

Used to calculate the velocity of flow in an open channel.

$$V = 1.49/n * R^{2/3} * S^{1/2}$$

V	=	average velocity in the channel (ft./sec.)
n	=	Manning's Roughness Coefficient (based on channel lining) (*Table 5-12, page V-118 for man-made channels*) (*Table 5-16, page V-135 for natural channels*)
R	=	hydraulic radius (feet) = A/P (A) = The cross-sectional area of the channel, (P) = the Wetted Perimeter (*Plate 5-28, page V=111 or Plate 5-38, page V-133*) (*a more comprehensive set of equations can be found in Table 5.2 on page V-6 of the Training Notebook*)
S	=	slope of the channel (feet/foot) = the change in elevation divided by the horizontal length of the channel (rise/run).

To calculate $R^{2/3}$ using a common scientific calculator:

1) enter the value of "R"
2) press the carot symbol "^"
3) enter the value of (⅔) or just use 0.667
4) press enter or equals

(Note: HP calculators differ slightly in the order of execution)

To calculate $S^{1/2}$ using a common scientific calculator:
$S^{1/2} = \sqrt{S}$ (the square root of S).

Note: $^2/_3$ = 0.667
½ = 0.5

Continuity Equation

$$Q = VA$$

Q	=	flow rate in the channel (cu. ft. / sec.)
V	=	average velocity in the channel (ft. / sec.) from Manning's Equation
A	=	cross-sectional area of the channel (sq. ft.)

Rational Method

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

$$Q = C * i * A$$

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

NRCS – TR-55 Method

Technical Release – 55, Urban Hydrology for Small Watersheds

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

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

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

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

Note: 1 square mile = 640 acres

Time of Concentration ESCH V-4

Overland Flow <300 feet

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

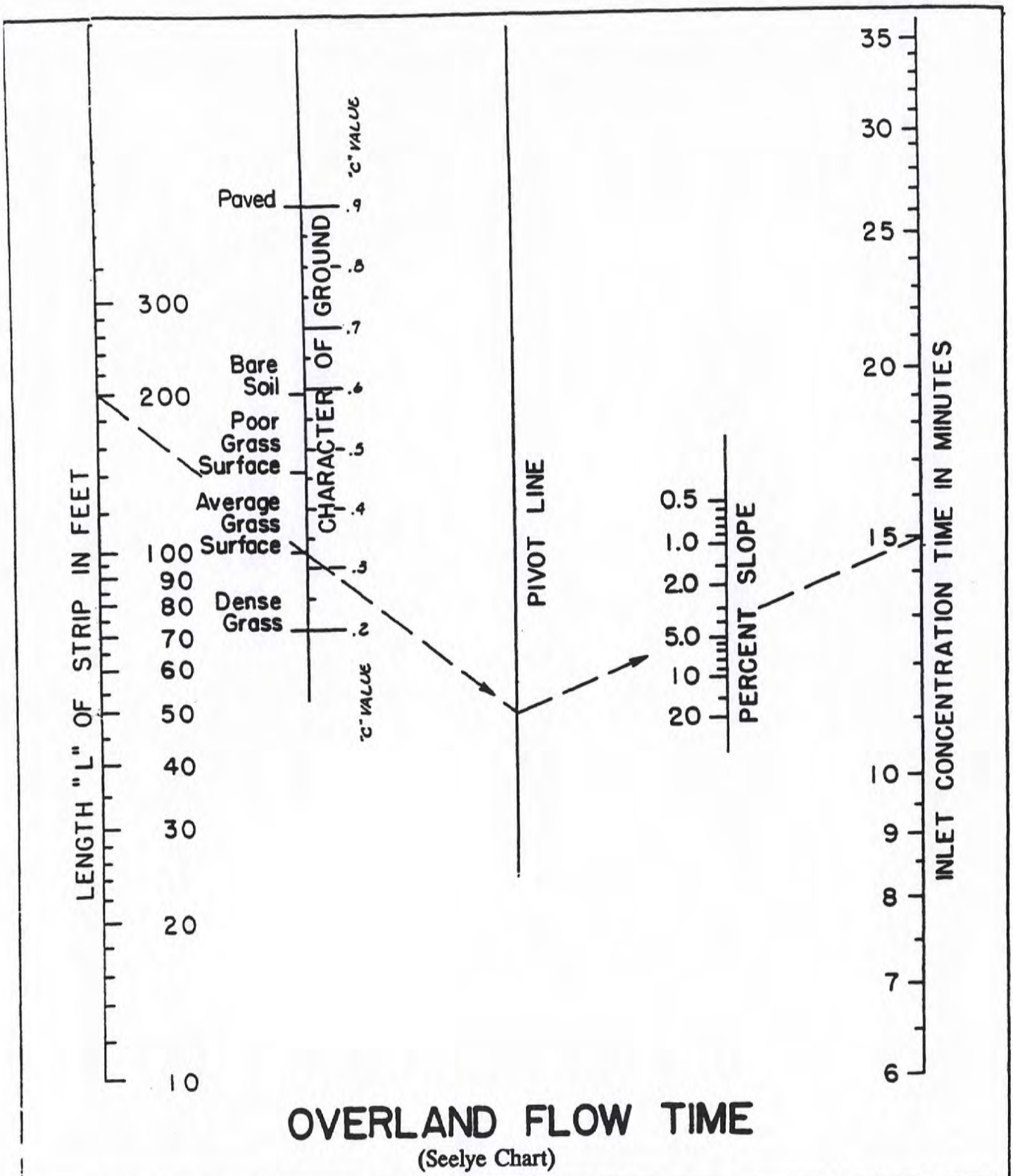
From ESCH V-11, Plate 5-1, Seelye Chart

Select on left vertical axis the Length = ( )feet

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

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

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



OVERLAND FLOW TIME
(Seelye Chart)

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

Plate 5-1

Shallow Concentrated Flow < 1000 feet

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

From ESCH V-11, Plate 5-2

Convert slope in % to slope in feet/foot:

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

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

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

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

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

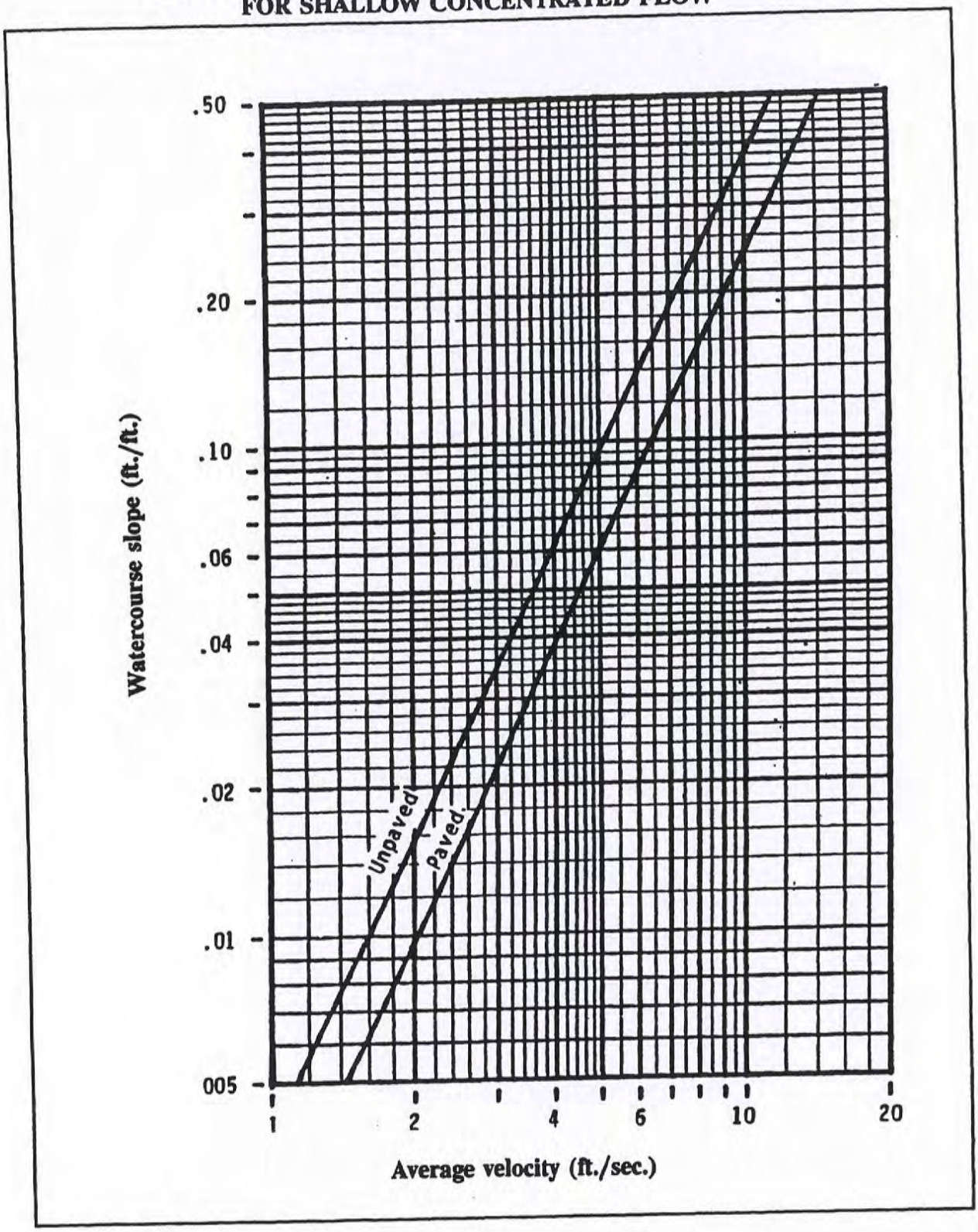
Average Velocity, V = ( )feet/second

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

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

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

AVERAGE VELOCITIES FOR ESTIMATING TRAVEL TIME FOR SHALLOW CONCENTRATED FLOW



Source: USDA-SCS

Plate 5-2

Channel Flow

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

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

On left vertical axis select Hydraulic Radius = ( )

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

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

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

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

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

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

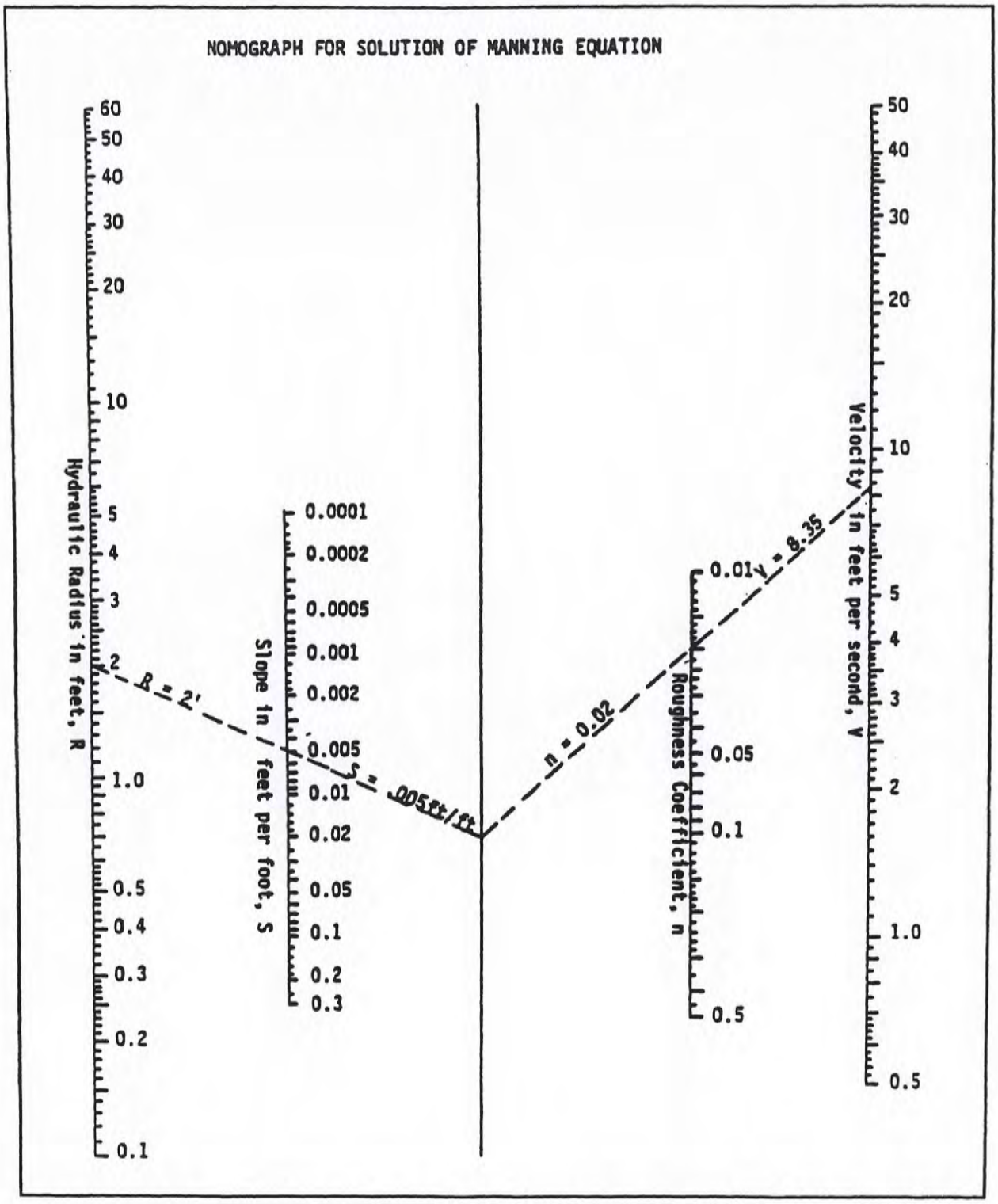
4. **What is the total time of concentration?**

Total Time of Concentration,

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

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

NOMOGRAPH FOR SOLUTION OF MANNING EQUATION



Source: VDOT

Plate 5-24