Module12: Channel Adequacy and Computations

Objectives

- Determine velocity in an open channel using Manning's Equation.
- Determine runoff capacity of an open channel using the Continuity Equation..
- Explain how each of the three basic inputs (channel lining, cross-sectional area, and slope) affect channel sizing.
- Verify channel adequacy using the combined Manning's/Continuity Equation.

12a. Channel Analysis

Channel adequacy for manmade channels:

> ***Manmade Channel*** Must convey the 10-year storm without overtopping and the 2-year storm without eroding.
>
> ***Pipes —*** Must convey the 10-year storm.

It is important for the reviewer to be familiar with the capacity (runoff/Q) and erodibility (velocity/V) requirements in order to verify the adequacy of stormwater conveyance channels and pipe systems associated with a development project. For more information on how conveyance channels are analyzed to determine if they meet these requirements, consult the VESCH, Chapter 5, Part III. Estimating peak runoff rates and runoff volumes are critical in the design and sizing of manmade channels and drainage ditches. Recall from Module 12 that a manmade channel must convey the 10-year storm without overtopping and the 2-year storm without eroding to meet the channel adequacy definition.

The next few sections of this module discuss the two principal equations that go into sizing manmade channels and ditches and verifying both capacity and velocity: Manning's Equation for determining velocity in an open channel and the Continuity Equation for determining runoff capacity of an open channel. Understanding these calculations and their inputs is critical to ensuring that the both the size of a channel and its lining are adequate to handle flow from a development project.

In general, verification of channel adequacy should include the following::

Channel geometry

A minimum of three channel cross-sections should be taken at a minimum spacing of 50' along the channel length downstream of the discharge point. The channel top of bank should be well defined and identifiable by field parameters such as a flattening or change in bank slope, flattened vegetation in the direction of flow, soil types or other obvious indicators of frequent flow levels. When the top of bank does not appear to be obvious, a hydrologic analysis of the contributory drainage area and the corresponding two (2)-year undeveloped peak discharge may be used to define the cross-sectional flow area using Manning's equation.

Channel lining

The channel lining material should be evaluated to determine the permissible velocities as found in Table 5-22 of the VESCH.

Slope

These include, for natural and manmade conveyance, respectively:

- **Channel slope**: Relative elevations should be taken along the channel length at the channel cross-sections in order to determine the average longitudinal slope of the channel.
- **Energy slope**: A hydraulic grade line calculation should accompany any analysis of an existing or proposed pipe system to verify that the flow is contained within the system during the ten (10)-year frequency storm.

Channel survey:

A designer must investigate each channel segment (reach) to accurately determine the relevant channel characteristics (e.g., slope, cross-section, roughness, downstream restrictions, etc.). This information is then used to to verify channel adequacy

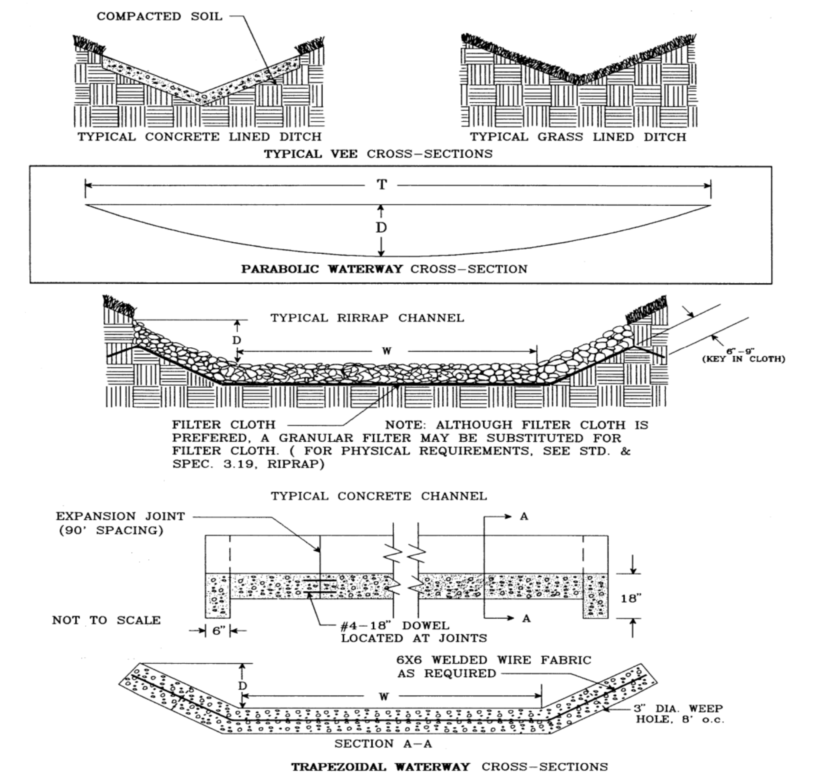
Part III of Chapter 5 of the VESCH should be consulted for additional information on determining channel adequacy and channel analysis.

12b. Reviewing Channel Design

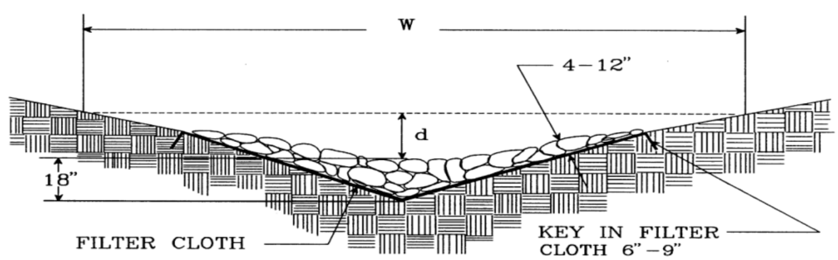
Refer to the Stormwater Conveyance Channel Erosion Standards and Specification 3.17 or the applicable Virginia Stormwater BMP Specification to verify correct design specifications. For example, ESC Specification 3.17 requires the following:

- Top width of parabolic and v-shaped channels not to exceed 30’
- Bottom width of trapezoid and grass lined not to exceed 15’
- Outlet protection
- Grass lined channels stabilized by the permanent seeding and/or sod specification
- Erosion netting
- Riprap (use Std & Specs)

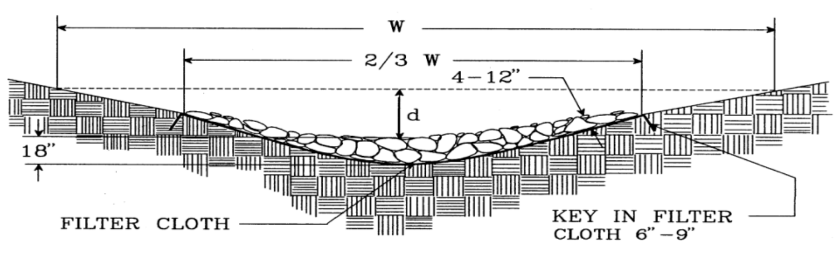
TYPICAL WATERWAY CROSS-SECTIONS



STONE-LINED WATERWAYS



V-SHAPED WATERWAY WITH STONE CENTER DRAIN
NOTE: A GRANULAR FILTER MAY BE SUBSTITUTED FOR FILTER CLOTH.



PARABOLIC WATERWAY WITH STONE CENTER DRAIN
NOTE: A GRANULAR FILTER MAY BE SUBSTITUTED FOR FILTER CLOTH.

12c. Manning's Equation

Manning's Equation is used to calculate the velocity of flow in an open channel:

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

Where:

V = the average velocity in the channel (feet/second)

n = Manning's roughness coefficient based on channel lining (dimensionless)

R = hydraulic radius = Area/Perimeter (feet)

A = wetted cross sectional area of flow (square feet)

P= wetted perimeter of the cross-sectional area of flow perpendicular to flow direction (feet)

s = slope of the channel (in feet/foot)

Manning's "n" Values

The first input into the Manning's Equation is the Manning's "n" value, also known as the Manning's roughness coefficient. The "n" value is a dimensionless number that is used to assign a value to the roughness of a channel. In general, smoother surfaces have lower "n" values and rougher surfaces have higher "n" values. Table 5-12 in the VESCH (page V-118) provides ranges of "n" values for channel linings (concrete and asphalt) and pipe linings (corrugated metal and concrete). Table 5-16 (page V-135) provides "n" values for natural channels. The VESCH presents a series of modifiers to be used with the values obtained from Table 5-16. These modifiers take into account characteristics such as channel irregularity, variation in channel cross sections, effect of obstructions, vegetation and flow conditions, and sinuosity. The VESCH also outlines the procedure for modifying the "n" value (pages V-123 and V-124).

Table 12.1 presents a series of "n" values for artificial and naturally-lined channels. An average "n" value used for sizing grass ditchlines is 0.05 (see Table 12.1, section IV, subset B). The *VDOT Drainage Manual* uses an "n" value of 0.05 for grass-lined channels on its series of channel charts.

Hydraulic Radius

In order to calculate the hydraulic radius of the channel (A/P), the cross-sectional area (A) of the channel and the wetted perimeter (P) need to be determined.

Area

The area (A) represents the cross-sectional area of the channel. There are three main types of channel cross-sections — vee, trapezoidal, and parabolic. Each of these cross sections has its own equation for determining area. These equations are presented in Plate 5-28 of the VESCH (page V-111).

Wetted Perimeter

The wetted perimeter (P) is the length of the channel cross-section that is in contact with the flow of water. Figure 12.1 illustrates this concept.

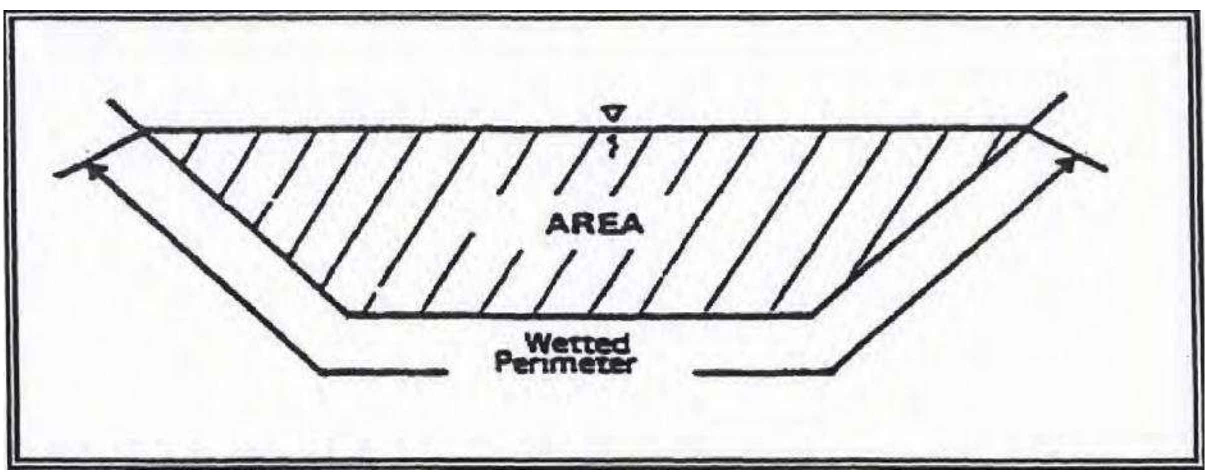


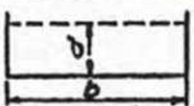
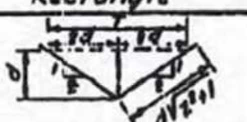
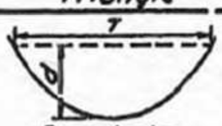
Figure 12.1 Wetted Perimeter

The equations for determining the wetted perimeter for several channel cross sections can be found in Table 12.2. Using the area and the wetted perimeter, the hydraulic radius (A/P) of the channel can be calculated. Plate 5-28 of the VESCH (page V-111) incorporates this into one step, providing an equation for the hydraulic radius of the three primary channels (v-shape, trapezoidal, and parabolic).

Slope

The final input into the Manning's equation is channel slope. This is calculated just like any other slope (rise/run). The slope of the channel relates to the elevation change in feet, divided by the length of the channel in feet, as taken from the plan.

Table 12.2 Equations for Channel Cross-Sections

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

Verifying the Permissible Velocity

Once the reviewer verifies the average velocity in the channel (V), the proposed channel lining can be evaluated for adequacy at that velocity. Table 5-22 (page V-140) in the VESCH provides a list of permissible velocities based on soil types for unlined earthen channels. In cases where the channel tends to meander, a reduction in permissible velocity is calculated using Table 5-23 (page V-141). Table 3.17-A (page DI-135) in the Stormwater Conveyance Channel section (Chapter 3) of the VESCH provides permissible velocities for grass-lined channels. If the velocity in the channel is less than the permissible velocity, then the channel design is considered to have adequate erosion resistance. If the velocity in the channel is higher than the permissible velocity, then the channel lining needs to be redesigned to provide additional erosion resistance.

12d. Continuity Equation

Once the cross-sectional area and the velocity of the channel are known, the capacity ("Q") can be determined using the Continuity Equation.

The Continuity Equation is:

$$Q = V \times A$$

Where,

Q = flow rate in the channel in cubic feet per second (cfs)

V = the average velocity in the channel (feet/second) from Manning's Equation

A = cross sectional area of the channel in square feet

The channel capacity (Q) should be able to accommodate the peak rate of runoff (Q) from the site (refer to Unit VIII and Unit IX for how to determine the peak rate of runoff). If the capacity of the channel is greater than the peak rate of runoff from the site, then the velocity should be calculated using the actual depth of flow.

12d. Understanding the Inputs

To verify the adequacy of channels associated with a development project, it is important to understand how each of the three basic inputs (channel lining, cross-sectional area, and slope) of channel design affect the outcome of the Manning's Equation.

Channel Lining

Channel Lining is inversely proportional to velocity in the Manning's Equation. A smoother channel has a faster flow than a rougher channel. This is made clear when considering the Manning's roughness coefficient ("n") values for concrete pipe (0.013), versus corrugated metal pipe (0.03). The flow through the concrete pipe is smoother, therefore, the "n" value is lower, and the velocity is higher. This same relationship occurs in open channels.

Cross-Sectional Area

The cross-sectional area of a channel is a function of the hydraulic radius in Manning's Equation. As depth in a given channel increases, the hydraulic radius increases, and the velocity increases. An increase in depth affects the area (A) of the channel, but does not affect the wetted perimeter (P). The result is an increase in the hydraulic radius (A/P).

All things being equal, a deep channel will convey water at a higher mean velocity (without erosion) than a shallow one. Consequently, the VESCH provides a way to correct the permissible velocity for a channel based on the average depth of flow. Plate 5-39 in the VESCH (page V-134) explains how to determine the correction factor based on the average depth of the channel. As a general rule, v-shaped ditches will convey water more quickly than trapezoidal or parabolic-shaped ditches.

Slope

Slope is directly proportional to velocity in the Manning's Equation. As slope increases, velocity increases and as slope decreases, velocity decreases.

Table 12.1 Manning's Roughness Coefficients (Source: U.S. DOT, Hydraulic Design Series No. 3

I. Closed Conduits	Manning's n Range[2]
A. Concrete pipes	0.011-0.013
B. Corrugated-metal pipe or pipe-arch.	
1. 2 2/3 by 1/2-in. corrugation (riveted pipe):[3]	
a. Plain or fully coated	0.024
b. Paved invert (range values are for 25 and 50 percent of circumference paved):	
(1) Flow full depth	0.021-0.018
(2) Flow 0.8 depth	0.021-0.016
(3) Flow 0.6 depth	0.019-0.013
2. 6 by 2-in. corrugation (field bolted)	0.03
C. Vitrified clay pipe	0.012-0.014
D. Cast-iron pipe, uncoated	0.013
E. Steel pipe	0.009-0.011
F. Brick	0.014-0.017
G. Monolithic concrete:	
1. Wood forms, rough	0.015-0.017
2. Wood forms, smooth	
3. Steel forms	
H. Cemented rubble masonry walls:	0.012-0.013
1. Concrete floor and top	
2. Natural floor	
I. Laminated treated wood	
J. Vitrified clay liner plates	
II. Open Channels, Lined[4] (straight lignment):[5]	0.015
A. Concrete with surfaces as indicated:	
1. Formed, no finish	0.013-0.017
2. Trowel finish	0.012-0.014
3. Float finish	0.013-0.015
4. Float finish, some gravel on bottom	0.015-0.017
5. Gunite, good section	0.016-0.019
6. Gunite, wavy section	0.018-0.022
B. Concrete, bottom float finished, sides as indicated:	
1. Dressed stone in mortar	0.015-0.017
2. Random stone in mortar	0.017-0.020
3. Cement rubble masonry	0.020-0.025
4. Cement rubble masonry, plastered	0.016-0.020
5. Dry rubble (riprap)	0.020-0.030
C. Gravel bottom, sides as indicated:	
1. Formed concrete	0.017-0.020
2. Random stone in mortar	0.020-0.023
3. Dry rubble (riprap)	0.023-0.033
D. Brick	0.014-0.017
E. Asphalt:	
1. Smooth	0.013
2. Rough	0.016
F. Wood, planed, clean	0.011-0.013
G. Concrete-lined excavated rock:	
1. Good section	0.017-0.020
2. Irregular section	0.022-0.027
III. Open Channels, excavated[4] (straight alignment,[5] natural lining):	
A. Earth, uniform section:	
1. Clean, recently completed	0.016-0.018
2. Clean, after weathering	0.018-0.020
3. With short grass, few weeds	0.022-0.027
4. In gravelly soil, uniform section, clean	0.022-0.025
B. Earth, fairly uniform section:	
1. No vegetation	0.022-0.025
2. Grass, some weeds	0.025-0.030
3. Dense weeds or aquatic plants in deep channels	0.030-0.035
4. Sides clean, gravel bottom	0.025-0.030
5. Sides clean, cobble bottom	0.030-0.040
C. Dragline excavated or dredged:	
1. No vegetation	0.028-0.033
2. Light brush on banks	0.035-0.050
D. Rock:	
1. Based on design section	0.035
2. Based on actual mean section:	
a. Smooth and uniform	0.035-0.050
b. Jagged and irregular	0.040-0.045
E. Channels not maintained, weeds and brush uncut:	
1. Dense weeds, high as flow depth	0.08-0.12
2. Clean bottom, brush on sides	0.05-0.08
3. Clean bottom, brush on sides, highest stage of flow	0.07-0.11
4. Dense brush, high stage	0.10-0.14

IV. Highway Channels and Swales with Maintained Vegetation[6] (values shown here are for velocities of 2 and 6 f.p.s.):	Manning's n Range[2]
A. Depth of Flow up to 0.7 foot:	
1. Bermudagrass, Kentucky bluegrass, Buffalograss:	
a. Mowed to 2-inches	0.07-0.045
b. Length 4n6 inches	0.09-0.05
2. Good stand, any grass:	
a. Length about 12-inches	
b. Length about 24-inches	0.18-0.09
3. Fair stand, any grass:	0.30-0.15
a. Length about 12-inches	
b. Length about 24-inches	0.14-0.08
B. Depth of flow 0.7-1.5 feet:	0.25-0.13
1. Bermudagrass, Kentucky bluegrass, Buffalograss:	
a. Mowed to 2-inches	
b. Length 4n6 inches	0.05-0.035
2. Good stand, any grass:	0.06-0.04
a. Length about 12-inches	
b. Length about 24-inches	0.12-0.07
3. Fair stand, any grass:	0.20-0.10
a. Length about 12-inches	
b. Length about 24-inches	0.10-0.06
V. Street and Expressway Gutters:	0.17-0.09
A. Concrete gutter, troweled finish	
B. Asphalt pavement:	0.012
1. Smooth texture	
2. Rough texture	0.013
C. Concrete Gutter with asphalt pavement:	0.016
1. Smooth	
2. Rough	0.013
D. Concrete pavement:	0.015
1. Float finish	
2. Broom finish	0.014
E. For gutters with small slope, where sediment may accumulate, increase above values of n by	0.016
	0.002
VI. Natural stream channels:[8]	
A. Minor streams[9] (surface width at flood stage less than 100 ft):	
1. Fairly regular section:	
a. Some grass and weeds, little or no brush	0.030-0.035
b. Dense growth of weeds, depth of flow materially greater than weed height	0.035-0.05
c. Some weeds, light brush on banks	0.035-0.05
d. Some weeds, heavy brush on banks	0.05-0.07
e. Some weeds, dense willows on banks	0.06-0.08
f. For trees within channel, with branches submerged at high stage, increase all above values by	*0.01-0.02*
2. Irregular sections, with pools, slight channel meander; increase values given in 1ane about	*0.01-0.02*
3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
a. Bottom of gravel. cobbles, and few boulders	0.04-0.05
b. Bottom of cobbles, with large boulders	0.05-0.07
B. Flood plains (adjacent to natural streams)	
1. Pasture, no brush:	
a. Short grass	0.030-0.035
b. High grass	0.035-0.05
2. Cultivated areas:	
a. No crop	0.03-0.04
b. Mature row crops	0.035-0.045
c. Mature field crops	0.04-0.05
3. Heavy weeds, scattered brush	0.05-0.07
4. Light brush and trees:[10]	
a. Winter	0.05-0.06
b. Summer	0.06-0.08
5. Medium to dense brush:[10]	
a. Winter	0.07-0.11
b. Summer	0.10-0.16
6. Dense willows, summer, not bent over by current	0.15-0.20
7. Cleared land with tree stumps, 100n150 per acre:	
a. No sprouts	0.04-0.05
b. With heavy growth of sprouts	0.06-0.08
8. Heavy stand of timber, a few down trees, little undergrowth:	
a. Flood depth below branches	0.10-0.12
b. Flood depth reaches branches	0.12-0.16
C. Major streams (surface width at flood stage more that 100 ft.): Roughness coefficient usually less than for minor streams of similar description on account of less effective resistance offered by irregular banks or vegetation on banks. Values of n may be somewhat reduced. Follow recommendation in publication cited[8] if possible. The value of n for larger streams of most regular section, with no boulders or brush, may be in the range of	0.028-0.033

12e. Channel Design

Selecting the proper channel is an iterative process by which the designer attempts to accommodate the flow from the site without exceeding the permissible velocity of the channel lining. The Manning's Continuity Equation is a useful tool in designing the cross-section of the channel to accommodate a known peak rate of runoff (Q). A combination of the Manning's and Continuity equations, the Manning's Continuity Equation is as follows:

$$\frac{Q \times n}{1.49 \times S^{1/2}} = A \times R^{2/3}$$

Using this equation, the designer can calculate the area of the proposed channel (right side of the equation) and compare it to the area required (left side of the equation), until both are equal. The left side of the equation incorporates the known Q for the designated frequency storm. To calculate the right side of the equation (AR-), it may prove useful to set up a table as follows:

Bottom Width	Depth	Area	Wetted Perimeter	Hydraulic Radius	$AR^{2/3}$

Using this table, the designer can vary bottom width and/or depth to come up with the desired cross-section (AR-).

Once the design area is known, the designer can use a variation of the Continuity Equation to verify that the designed channel will not erode:

$$V_{(2,10)} = \frac{Q_{(2,10)}}{A_{(2,10)}}$$

In this case, the Q and the A (for the designated frequency storm) arc known and can be used to find V.

Notes

Module 12 Work Problems

A plan reviewer needs experience manipulating the Manning's Equation and the Continuity Equation in order to become proficient at verifying the capacity and erodibility of ditchlines and other manmade earthen channels. Several examples of ditch computations are included in this module to help make reviewers comfortable with using these equations.

Proficiency in using the Manning's Equation is especially important because it is used to calculate the travel time for the channel flow portion of the time of concentration (for more information on time of concentration, refer to Modules 10 and 11). The time of concentration, in turn, is used to calculate peak discharge using the rational and graphical peak discharge methods (Module 10 and Module 11, respectively).

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)?

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

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:

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

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

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

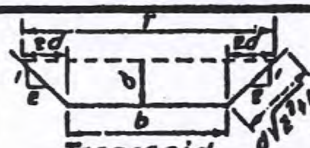
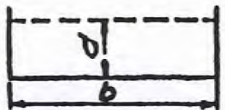
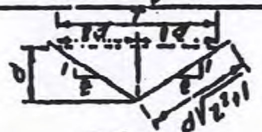
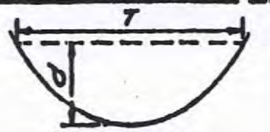
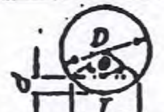
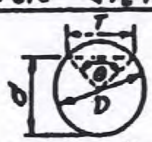
p = (   ) feet + 2 x (   ) feet x [(   )^2 + 1]$^{1/2}$ = (   ) feet

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 $2\sqrt{d(D-d)}$

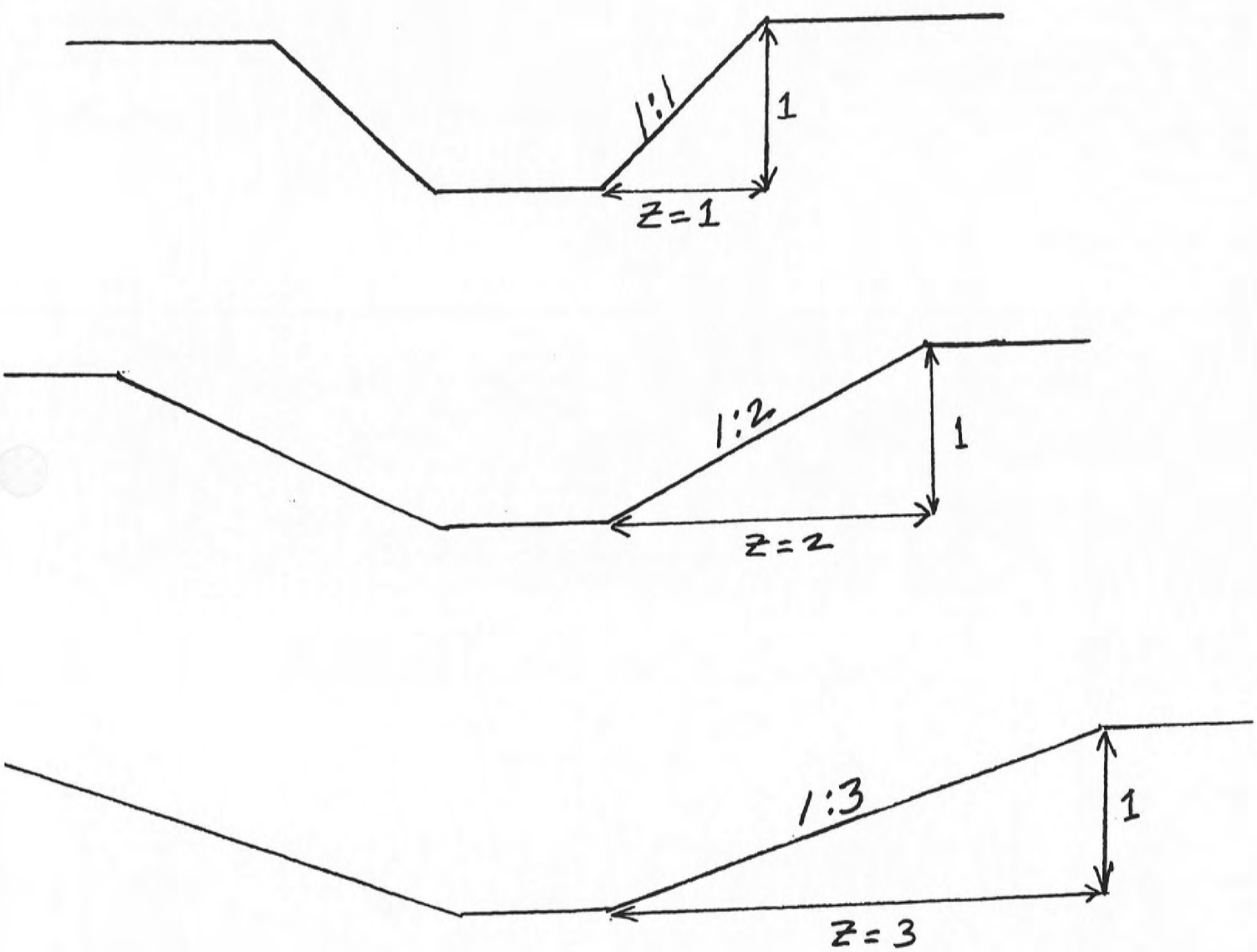
[1] Satisfactory approximation for the interval $0 < \frac{d}{T} \leq 0.25$
When $d/T > 0.25$, use $p = \frac{1}{2}\sqrt{16d^2+T^2} + \frac{T^2}{8d}\sinh^{-1}\frac{4d}{T}$

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

4.6.2007

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
<u>Canals and ditches</u>:				
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
<u>Natural Stream Channels</u>:				
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.)