Module 12: Channel Evaluation

Learning Objectives

At the end of this module, you will be able to:

- 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 and Inputs

Concentrated runoff discharged to a channel from a proposed site has the potential to cause erosion and/or flooding due to the customary land cover changes and resulting increases in runoff associated with development. Compliance requirements and/or verification methods are specific to the type of channel receiving runoff. Refer to Module 5 for the regulatory requirements for water quantity.

Part V, Article 3 of the VESM Regulation requires verification of:

- Channel capacity for all channels and
- Channel stability for manmade channels.

Compliance verifications may also be required for:

- Channel improvements and restored channels receiving discharges and
- Natural channels receiving discharges, if required by a VESMP authority.

There is more than one method that can be used for these verifications; however, the information that must be obtained for an evaluation includes the inputs described in the section below.

CHANNEL SURVEY

The hydraulic calculations are simplified by assuming the channel can be divided into segments in which uniform flow exists. Uniform flow describes a condition where the depth of flow, cross-sectional area, runoff velocity, and flow at every section of the channel segment are constant. In reality, these conditions are seldom met. The channel can, however, be divided into segments which have similar cross-sections and slope, and the flow can be considered at one point in time, such as the peak flow, when the quantity of flow would be more or less constant.

Appendix A of the Virginia Stormwater Management Handbook (VSWHB) should be consulted for additional information on determining channel adequacy and channel analysis.

Once a channel is divided into fairly uniform segments, each channel segment (or reach) must be evaluated to accurately determine the relevant channel characteristics (e.g., slope, representative cross-sectional area, channel lining roughness, downstream restrictions, etc.).

This information is then used to verify compliance. VSWHB recommends at the very minimum, three channel cross-sections 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 contributing 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.

PERMISSIBLE TRACTIVE FORCE (PERMISSIBLE SHEAR) METHOD

The VDOT Drainage Manual Chapter 7 (https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/technical-guidance-documents/location-and-design/migrated/drainagemanual/chapter7_acc10172023_PM.pdf) contains the Permissible Tractive Force, also known as the Permissible Shear Method, that provides a physical-based model for the erosion processes in a channel. The Tractive Force (Permissible Shear) Method considers the physical factors of bed material, channel geometry, depth, and velocity of flow.

The average tractive force formula is:

$$\tau_O = 62.4 R S_O$$

Where:

τ_O = Average tractive force, lbs/ft^2

R= Hydraulic radius, ft.

S_O= Channel slope ft/ft.

Shear Stress in Bends

Flow around a bend can impose higher shear stresses on the channel bottom and sides as compared to a straight channel. The Following equation gives the maximum shear stress in a bend.

$$\tau_b = K_b \tau_{max}$$

Where:

τ_b = Maximum bend shear stress, lb/ft^2

K_b = Ration of channel bend to bottom shear stress

τ_{max} = Shear stress in straight channel at maximum depth, lb/ft^2

The ratio of channel bend to bottom shear stress (K_b) is a function of the channel curvature to the top (water surface) width, R_c/T. K_b can be determined using the following equation:

$$K_b = 2.00 \qquad R_c/T \leq 2$$

$$K_b = 2.38 - 0.206(R_c/T) + 0.0073(R_c/T)^2 \qquad 2 < R_c/T < 10$$

$$K_b = 1.05 \qquad 10 \leq R_c/T$$

Where:

R_c = radius of curvature of the Centerline of the bend, ft.

T= channel top (water surface) width, ft.

For more detailed information about the Permissible Tractive Force (Permissible Shear) Method reference the VDOT Drainage Manual Chapter 7. This is one acceptable method for evaluating channel protection criteria; however, we will cover in greater detail the Maximum Permissible Velocity Method and it's use for evaluating channel protection.

MAXIMUM PERMISSIBLE VELOCITY METHOD

Both the capacity of the channel and the velocity of flow are functions of the channel lining, cross-sectional area, and slope. The channel must have a cross-section and lining that will provide sufficient capacity, erosion resistance, and stability to convey the runoff.

The next sections of this module discuss the two principal equations of the Maximum Permissible Velocity Method, which is one of the common methods used to size and design manmade channels and verify channel capacity and lining stability:

- Manning's Equation for determining velocity in an open channel and
- Continuity Equation for determining runoff capacity of an open channel.

Understanding these calculations and their inputs is critical for compliance verification. Other design/verification methods that may be used are beyond the capacity of this participant guide.

MANNING'S EQUATION

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

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

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)

Area

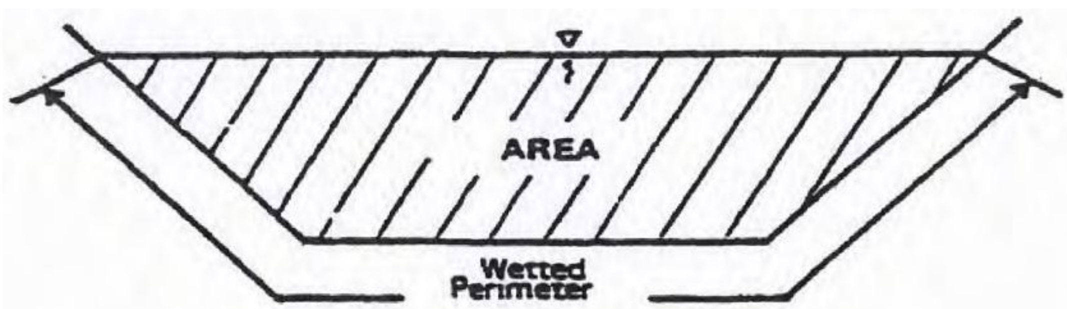
The area (A) represents the cross-sectional area of the channel. The cross-sectional area of a channel is a function of the hydraulic radius in Manning's Equation. As depth in a given channel increases, the hydraulic radius increases, and the velocity increases. An increase in depth affects the area (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. Therefore, a designer may adjust the maximum permissible velocity based on the depth of flow. As a plan reviewer, it is important to review the source of any correction factor chosen by a designer to ensure accuracy.

Each of three main types of channel cross-sections — vee, trapezoidal, and parabolic has its own equation for determining area. These equations are presented in Table C-ECM-09-6, in Chapter 7, part 7.4, C-ECM-09, section 10.0 Appendix C-ECM-09-b of the VSWHB. As a general rule, v- shaped ditches will convey water more quickly than trapezoidal or parabolic-shaped ditches.

Wetted Perimeter

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

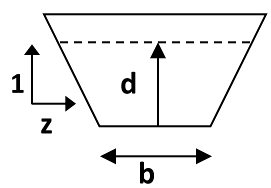
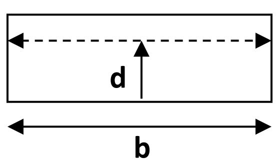
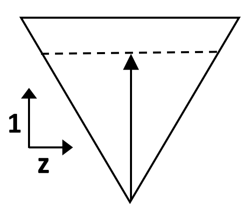


Hydraulic Radius

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

The equations for determining the wetted perimeter for several channel cross-sections can be found in Table 12-1 and Table 12-2. Using the area and the wetted perimeter, the hydraulic radius (A/P) of the channel can be calculated.

Table 12-1: Equations for Primary Channel Cross-Sections

Section	Area A	Wetted Perimeter P	Hydraulic Radius r = A/P	Top Width T
	$bd + zd^2$	$b + 2d\sqrt{z^2+1}$	$\frac{bd + zd^2}{b + 2d\sqrt{z^2+1}}$	$b + 2zd$
	bd	$b + 2d$	$\frac{bd}{b + 2d}$	b
	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$

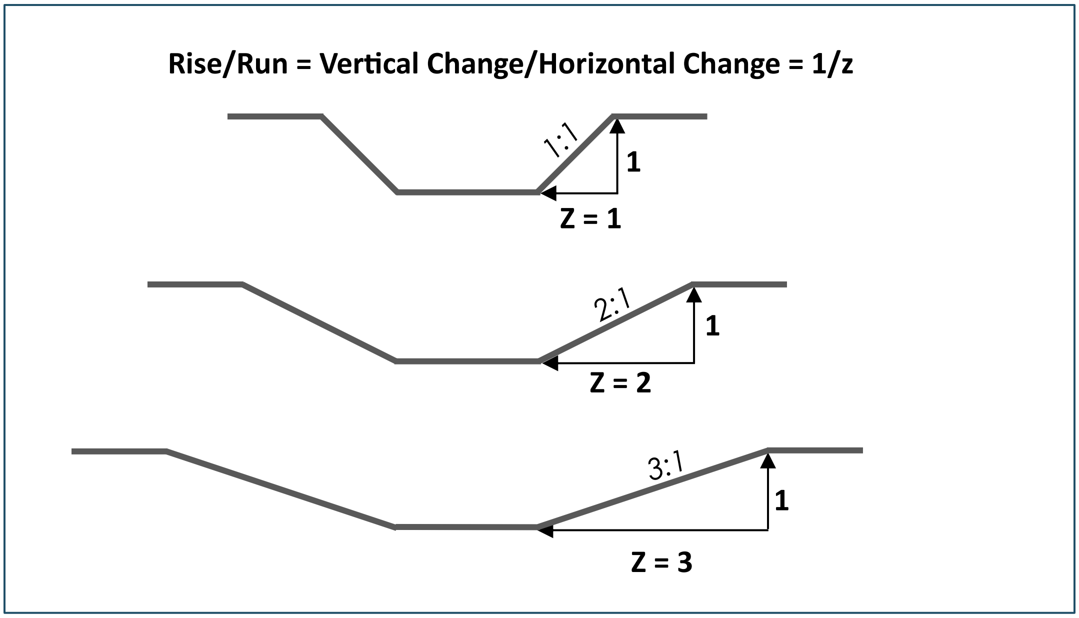
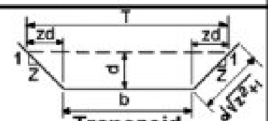
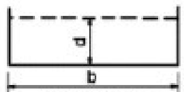
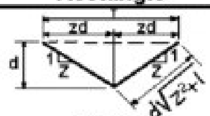
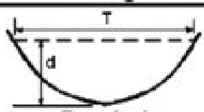
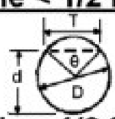


Figure 12-1: Channel Side Slopes

Table 12-2: Equations for Channel Cross-Sections

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

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

[2] $\theta = 4\sin^{-1}\sqrt{d/D}$

[3] $\theta = 4\cos^{-1}\sqrt{d/D}$

[2], [3]: Insert θ in degrees in above equations

National Engineering Handbook, Section 5, ES-33

Channel Slope (Longitudinal)

The final input into the Manning's equation is channel slope. This is calculated just like any other slope (rise/run) and relates to the elevation change in feet, divided by the length of the channel in feet, as taken from the plan. The slope of the channel is generally fixed by the topography and proposed route of the channel. A field survey can provide accurate information on slope. Slope is directly proportional to velocity in the Manning's Equation. As slope increases, velocity increases, and as slope decreases, velocity decreases.

For natural and manmade conveyance, respectively:

- **Channel slope**: Relative elevations should be taken along the channel length at the channel cross-sections 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 Lining Characteristics (Manning’s n)

Channel linings’ susceptibility to erosion can be estimated using the roughness coefficient known as the Manning's "n" value or 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. Channel lining is inversely proportional to velocity in the Manning's Equation. In general, smoother surfaces have lower "n" values, and rougher surfaces have higher "n" values. On the following pages, Table 12-3 through Table 12-6 provide Manning’s “n” values for various surfaces. The VDOT Drainage Manual uses an "n" value of 0.05 for grass-lined channels.

Manning’s “n” values, as well as modifiers to account for the channel characteristics, are available in many publications. Some examples are included on the following pages. As a plan reviewer, you should verify the Manning’s “n” value selected is appropriate based on the channel characteristics.

Table 12-3: Manning's Roughness Coefficients (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)	
C. Gravel bottom, sides as indicated:	0.020-0.030
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

Table 12-4: Manning's "n" Values for Pipes, Canals, and Ditches

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.

Table 12-5: Manning's "n" Values for Natural Stream Channels

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.				

Table 12-6: Manning's "n" Values for Select Channel Lining Materials

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

Verifying the Permissible Velocity

The velocity of runoff, assuming uniform flow for a channel segment, is calculated using Manning's equation and the inputs discussed earlier. This calculated velocity is compared to known permissible velocities associated with specific channel linings. These permissible velocities reflect the maximum velocities that a specific channel lining can tolerate without eroding. 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 would be considered inadequate in terms of erosion resistance. VSWHB contains tables of permissible velocities that are also reproduced on the following pages.

Table 12-7: Permissible Velocities for Grass-Lined Channels
(Table C-ECM-15-2, Chapter 7, Section 7.4, C-ECM-15 Outlet Protection, VSWHB)

Table C-ECM-15-2 Permissible Velocities for Grass-Lined Channels			
Channel Slope	**Lining**	**Erosion-Resistant Soil Velocity (ft/s)**	**Easily Eroded Soil Velocity (ft/s)**
0 – 5%	Bermudagrass	6	4.5
	Reed canarygrass Tall fescue Kentucky bluegrass	5	3.75
	Grass-legume mixture	4	3
	Red fescue Redtop Annual Lespedeza Small grains Temporary vegetation	2.5	1.875
5 – 10%	Bermudagrass	5	3.75
	Reed canarygrass Tall fescue Kentucky bluegrass	4	3
	Grass-legume mixture	3	2.25
>10%	Bermudagrass	4	3
	Reed canarygrass Tall fescue Kentucky bluegrass	3	2.25

Source: Schwab, G., et al., 1966

Note: In the table above, there are two different permissible velocities for grass-lined channels based on the erosivity of the soils. Both the designer and plan reviewer should verify the correct permissible velocity is chosen based on the site soil characteristics. Easily erodible soils' permissible velocities are reduced by 25%.

Table 12-8: Permissible Velocities for Unlined Earthen Channels
(Table C-ECM-15-3, Chapter 7, Section 7.4, C-ECM-15 Outlet Protection, VSWHB)

Table C-ECM-15-3 Permissible Velocities for Earth Linings	
Soil Types	**Permissible Velocities (ft/s)**
Fine Sand (non-colloidal)	2.5
Sandy Loam (non-colloidal)	2.5
Silt Loam (non-colloidal)	3.0
Ordinary Firm Loam	3.5
Fine Gravel	5.0
Stiff Clay (very colloidal)	5.0
Graded, Loam to Cobbles (non-colloidal)	5.0
Graded, Silt to Cobbles (colloidal)	5.5
Alluvial Silts (non-colloidal)	3.5
Alluvial Silts (colloidal)	5.0
Coarse Gravel (non-colloidal)	6.0
Cobbles and Shingles	5.5
Shales and Hard Plans	6.0

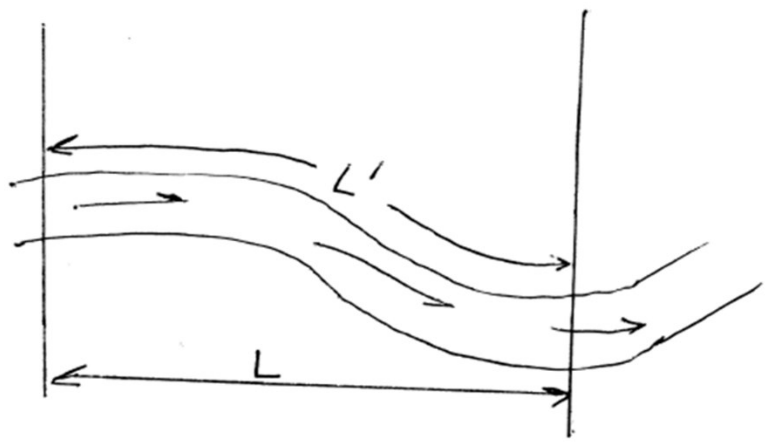
Source: Schwab, G., et al, 1966

Table 12-9: Reduction in Permissible Velocity Based on Sinuosity

REDUCTION IN PERMISSIBLE VELOCITY BASED ON SINUOSITY

Sinuosity*	Maximum Percent Reduction in Permissible Velocity
Slight (1.0 to 1.2)	5%
Moderate (1.2 to 1.5)	13%
Very Sinuous (1.5 and greater)	22%

* Sinuosity - degree of curvature of channel.



Sinuosity = L'/L

Source: Chow

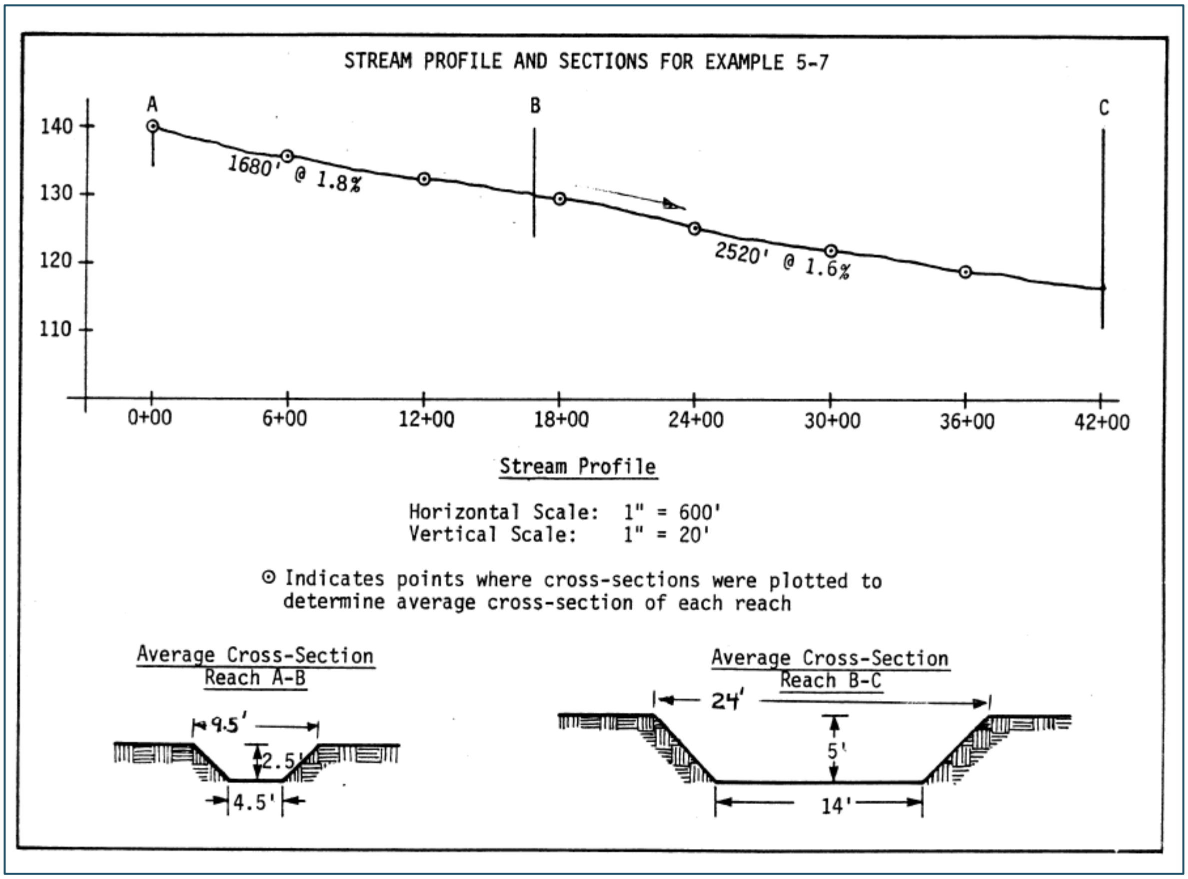


Figure 12-2. Example Stream Profile and Sections

Exercise:

The channel depicted above has been broken into two reaches. Reach AB has been analyzed at three cross-sections (Sta 0+00, Sta 6+00 and Sta 12+00) that are each 600 feet apart. Reach BC has been analyzed at four cross-sections that are also each 600 feet apart. The average cross-section for each reach is shown in the two cross-sectional diagrams.

The entire reach of the channel analyzed, between points A and C, is 4,200 feet. This is represented by the stations along the horizontal axis labeled every 600 feet. Between point A and point C, the elevation decreases from 140 feet to 120 feet (i.e. a 20-foot decrease in elevation).

(1) Assume bankfull flow, earth bottom and rubble sides, and a Manning's Roughness coefficient (n) of 0.03. What is the velocity for reach AB and the velocity for reach BC?

(2) If the channel lining is equivalent to coarse gravel, what is the permissible velocity?

(3) Would the channel erode under bankfull conditions?

(4) Would the channel erode during the 2-year design storm flow? Assume the 2-year depths are 1.75 feet for reach AB and 3.5 feet for reach BC.

12b. 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.

Continuity Equation:

$$Q = V \times A$$

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

Discharge Equation is obtained by substituting the Manning's equation into the Continuity equation:

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

Recall Manning's Equation:

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

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 Modules 9 and 10 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.

Refer back to the previous exercise (page 21) to evaluate channel capacity:

(5) What flow rate can the channel accommodate? Evaluate both reach AB and reach BC.

12c. Channel Computations Summary

It is important for the reviewer to be familiar with the capacity and erodibility requirements (see Module 5) in order to verify the adequacy of stormwater conveyance channels. Estimating peak runoff rates and runoff volumes as covered in Modules 9 and 10 are critical in the design and evaluation of channels for water quantity compliance.

Plan reviewers must evaluate the analyses of channels for both flow capacity and stability of channel lining (erosion prevention). Channel capacity computations must be evaluated for all channel types that receive discharges. Onsite channels and conveyance systems are evaluated to ensure that flows are contained and that channel linings will not erode. Channels that receive discharges from a proposed development must be evaluated from a site's discharge point to a downstream point defined by the regulations (limits of analysis). All channels must be evaluated for compliance with flood protection requirements, and manmade channels must be evaluated for erodibility. Manmade channels designed as part of a project (for water quality or water quantity) must also adhere to design specifications (Stormwater Conveyance Channel Construction BMPs, C-ECM-09 or Post-Construction BMP, P-CNV-01 Grass Channels).

In general, channel capacity is evaluated for the peak flow rate from the 10-year 24-hour storm for all channel types, and channel (lining) stability is evaluated for manmade channels for the peak flow rate from the 2-year 24-hour storm. Channel protection for natural channels is met with compliance with the energy balance equation (discussed in Module 11) at the discharge point and does not require downstream analysis unless program authorities establish more stringent requirements. Flood protection for natural channels requires a downstream analysis to ensure capacity requirements are met for the 10-year 24-hour storm from the discharge point to the limits of analysis (see Module 5).

More information on how to perform and evaluate channel analyses can be found in these references:

DEQ Certification Course Participant Guide: Stormwater Management for Plan Reviewers

VSWHB

Construction BMP Specification C-ECM-09 (Stormwater Conveyance Channels)

The basic components that plan reviewers should evaluate for channel and flood protection compliance are as follows:

- Peak flow estimation for existing conditions (various methods all require check of inputs as described earlier: rainfall, watershed characteristics including soils, land cover, topography)
- Peak flow estimation for proposed conditions (same as above except proposed conditions must be accurately represented)
- Determination if flows are confined within channel (without contributing to or causing localized flooding)

  i) Channel segments or reaches that are fairly uniform (in terms of longitudinal slope, cross-sectional geometry, roughness) must be identified between the discharge point and the downstream limits of analysis (GIS, topographic map, field survey)

  ii) Sufficient cross-sections are then selected along each channel segment for adequate representation

  iii) Relevant channel characteristics within each channel segment should be identified

    (1) Slope (longitudinal elevation change)

      (a) Significant changes in grade should be identified

    (2) Cross-sectional geometry

      (a) Identified with a plan view (each cross-section identified and labeled) and profiles for each cross-section (showing channel and floodplain)

    (3) Channel and floodplain roughness (estimated with Manning's n coefficient)

      (a) A separate Manning's n should be provided for the channel and the floodplain at each cross-section

  iv) Determination of elevations for pre- and post-development conditions

    (1) Output of modelling, which can be performed using various methodologies

    (2) Elevations should be shown with profiles for each cross-section

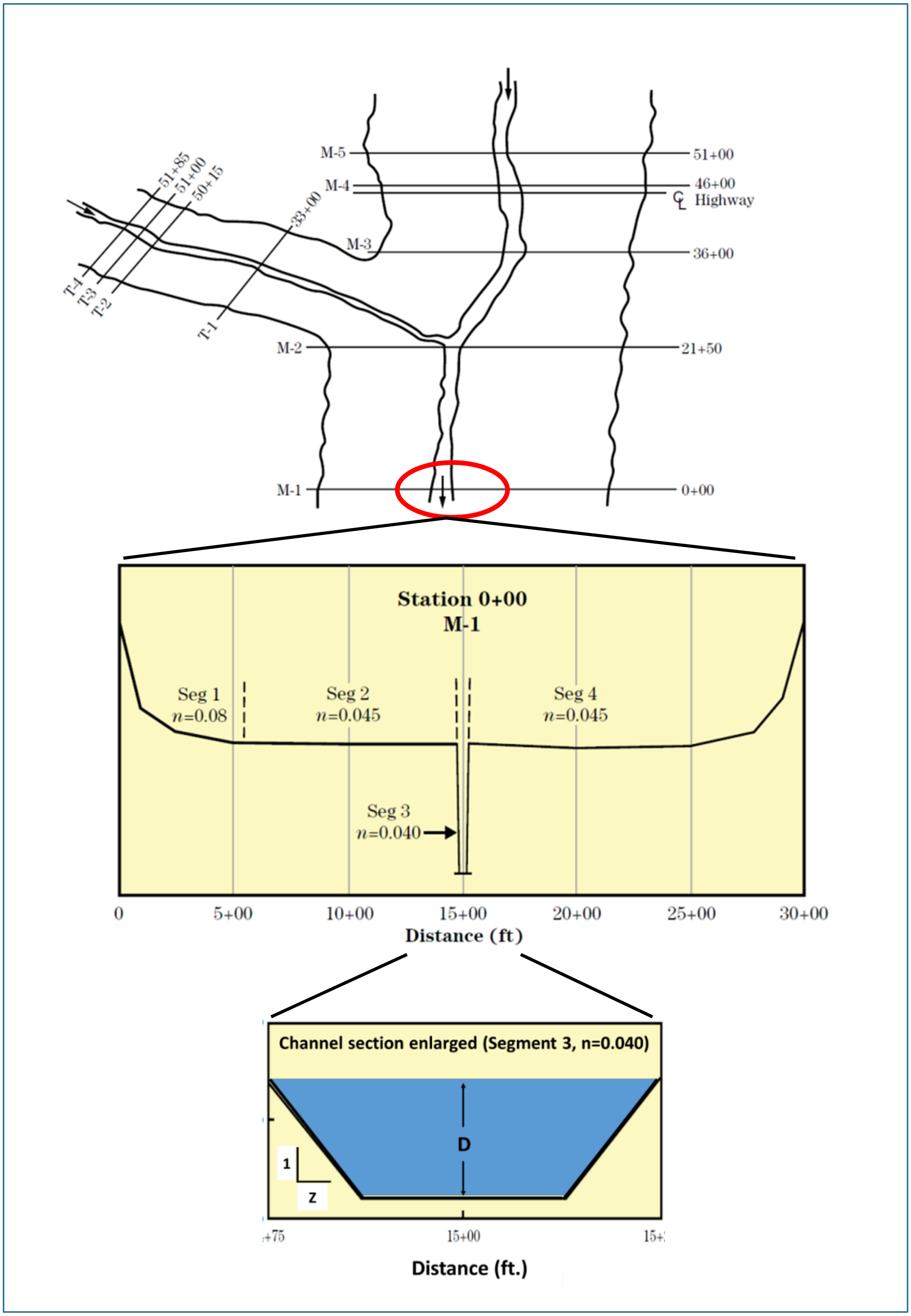


Figure 12-3: Example Downstream Channel Profile and Cross-Sections

Downstream channel analysis for water quantity compliance is shown in the next few figures. Included here is the stream profile from the discharge point to the limits of analysis with cross-section stations labeled, the cross-section profiles for each station, and the channel adequacy inputs and calculated values for the first and last of the cross-section stations. Inputs and calculated values for only two stations are presented below. The complete set of cross-section station data and calculations would be submitted for water quantity compliance. Downstream channel analysis would be expected to show compliance to the limit of analysis with flood protection and, if applicable, channel protection requirements.

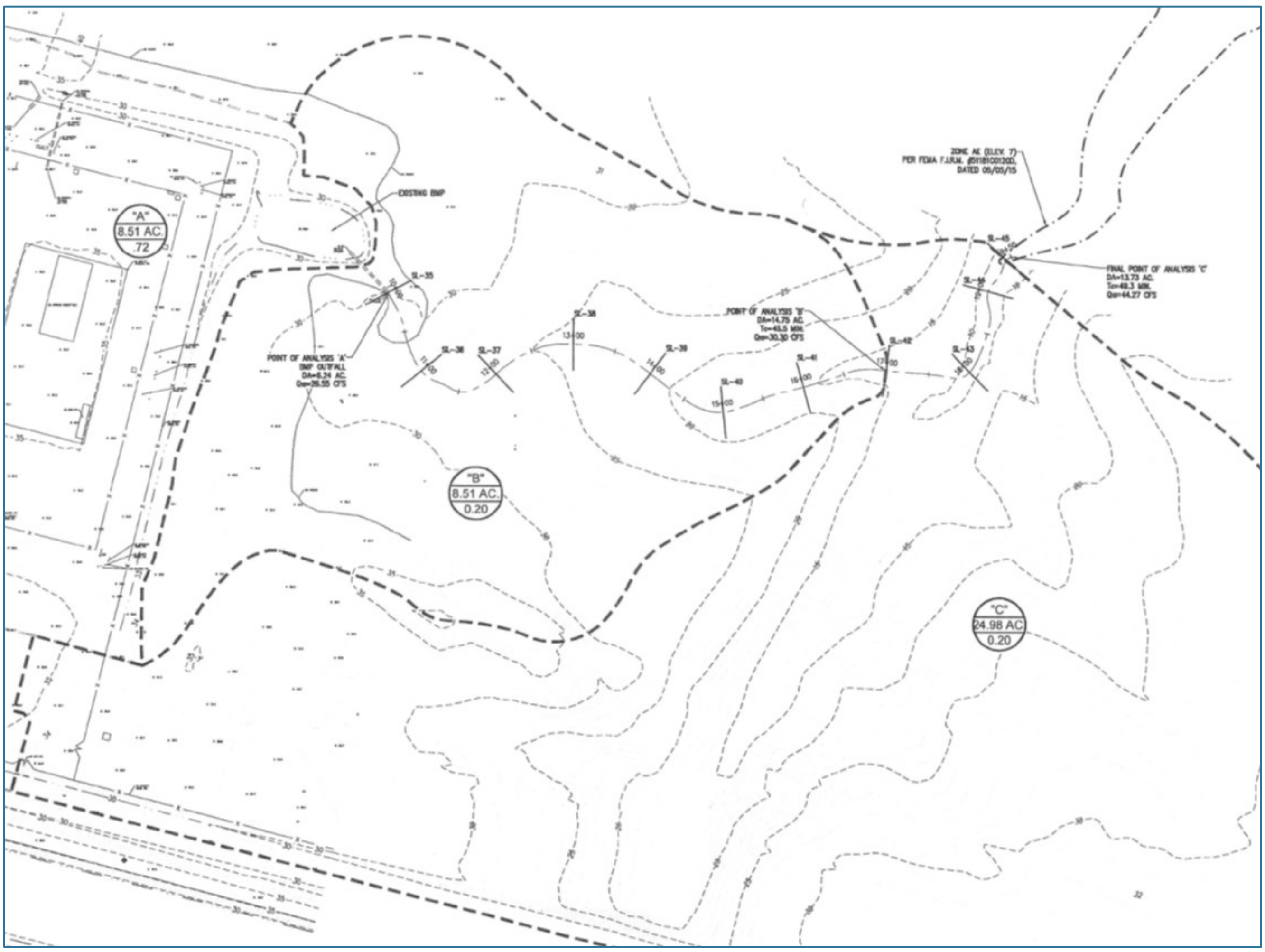


Figure 12-4: Downstream Channel to Limits of Analysis (Cross-section stations indicated)

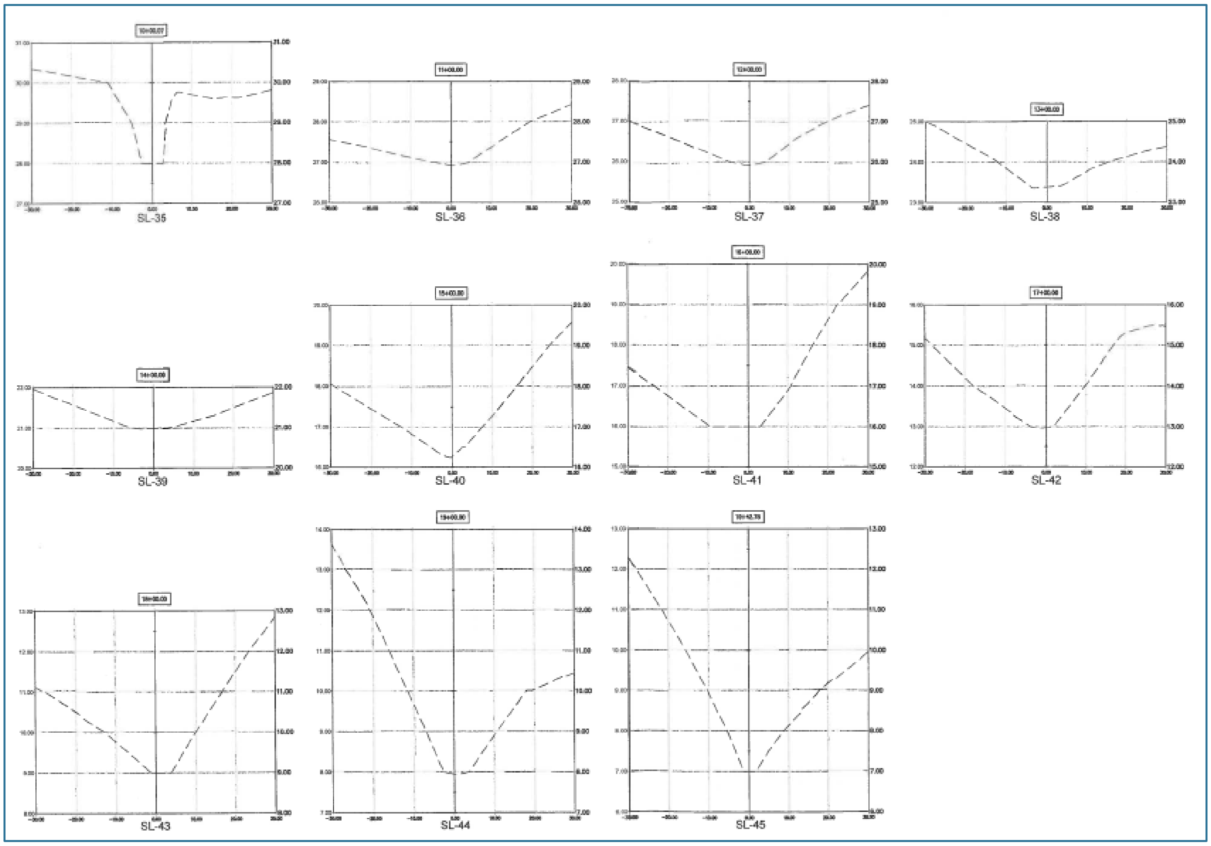


Figure 12-5: Downstream Channel Cross-Sections

> Typically, hydrologic channel routing techniques used by designers involve the continuity equation and some linear or curvilinear relation between storage and discharge within the channel.

Channel Report

Hydraflow Express Extension for Autodesk® AutoCAD® Civil 3D® by Autodesk, Inc.

Tuesday, Nov 28 2017

Channel Adequacy - Sta. 10+00 (10 Yr Storm)

User-defined

Invert Elev (ft)	= 28.00
Slope (%)	= 0.25
N-Value	= 0.022

Calculations

Compute by:	Known Q
Known Q (cfs)	= 26.55

Highlighted

Depth (ft)	= 1.13
Q (cfs)	= 26.55
Area (sqft)	= 9.00
Velocity (ft/s)	= 2.95
Wetted Perim (ft)	= 11.04
Crit Depth, Yc (ft)	= 0.77
Top Width (ft)	= 10.30
EGL (ft)	= 1.27

(Sta, El, n)-(Sta, El, n)...

(0.00, 30.00)-(6.00, 29.00, 0.022)-(7.50, 28.00, 0.022)-(14.00, 28.00, 0.022)-(15.00, 29.00, 0.022)-(18.00, 29.75, 0.022)

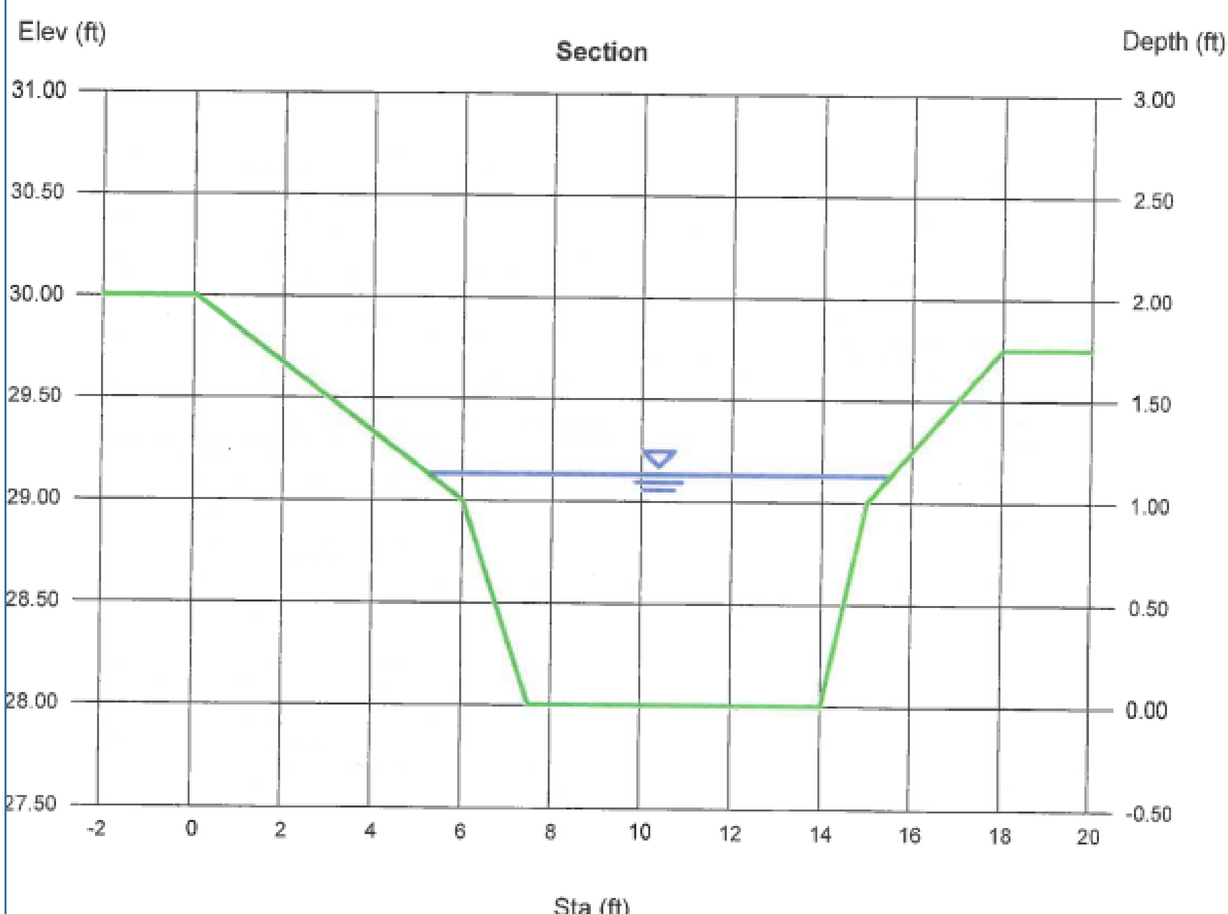


Figure 12-6: Downstream Channel Analysis Report Cross-section SL-35

Channel Report

Hydraflow Express Extension for Autodesk® AutoCAD® Civil 3D® by Autodesk, Inc. Tuesday, Nov 28 2017

Channel Adequacy - Sta. 19+43 (10 Yr Storm)

User-defined

Invert Elev (ft)	= 7.00
Slope (%)	= 3.50
N-Value	= 0.022

Calculations

Compute by:	Known Q
Known Q (cfs)	= 44.27

Highlighted

Depth (ft)	= 0.71
Q (cfs)	= 44.27
Area (sqft)	= 5.72
Velocity (ft/s)	= 7.75
Wetted Perim (ft)	= 11.75
Crit Depth, Yc (ft)	= 1.01
Top Width (ft)	= 11.60
EGL (ft)	= 1.64

(Sta, El, n)-(Sta, El, n)...

(0.00, 10.70)-(4.00, 10.00, 0.022)-(10.00, 9.00, 0.022)-(14.50, 8.00, 0.022)-(18.00, 7.00, 0.022)-(22.50, 7.00, 0.022)-(29.00, 8.00, 0.022)
-(38.00, 9.00, 0.022)-(50.00, 10.00, 0.022)

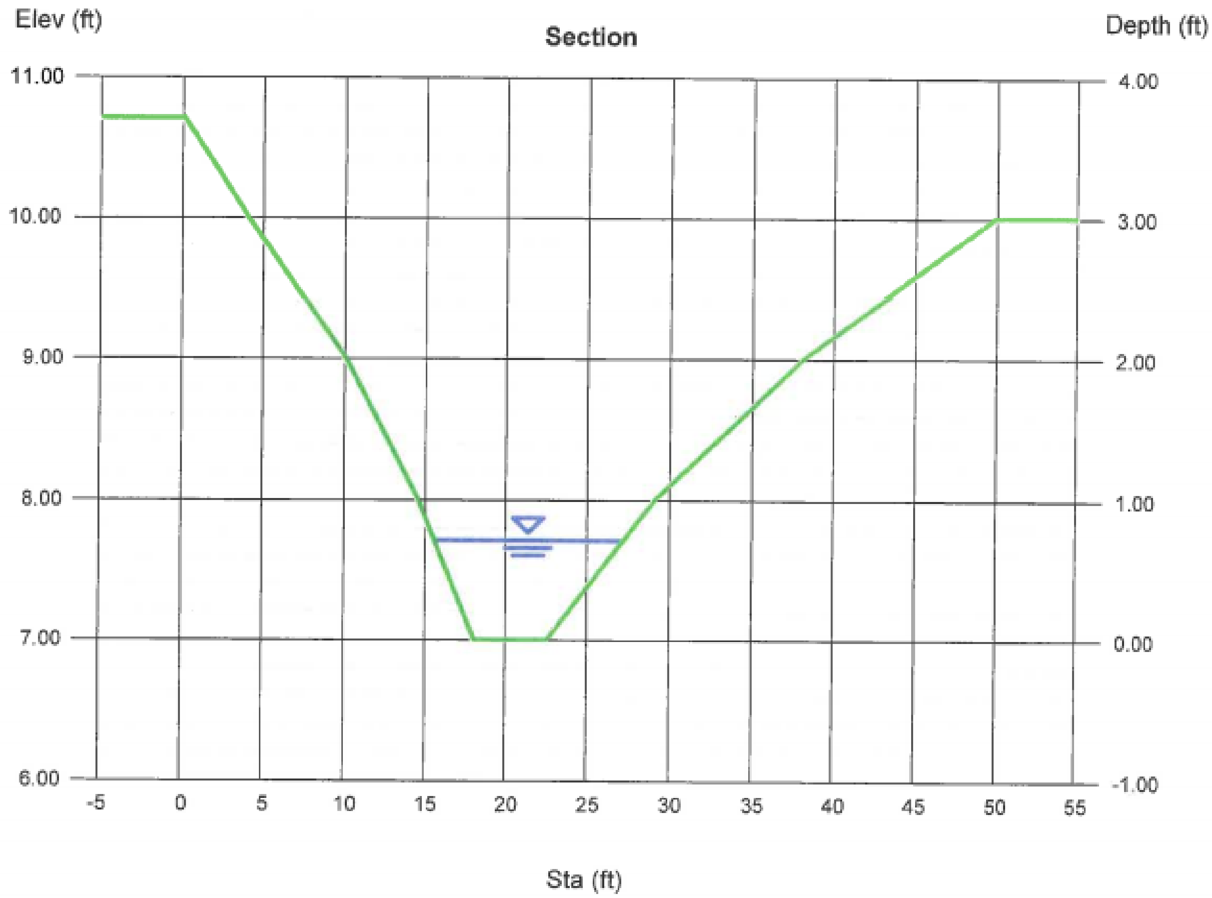


Figure 12-7: Downstream Channel Analysis Report Cross-section SL-44

12d. Reviewing Channel Design

Refer to the C-ECM-09 Stormwater Conveyance Channel specification or the applicable post-construction BMP (P-BMP) specification in the VSWHB to verify correct design specifications. The most common types of channels are vee, parabolic, and trapezoidal in shape. For example, C-ECM-09 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 (C-ECM-15)
- Appropriate channel lining that can withstand runoff velocity without erosion (based on maximum permissible velocities or permissible shear)
- Grass-lined channels stabilized by the permanent seeding and/or sod specification
- Erosion netting
- Riprap (C-ECM-13)

Selection of the proper channel design is a trial-and-error process by which the designer attempts to accommodate the flow without exceeding the maximum permissible velocity or permissible shear for the lining. For grass-lined channels, the maximum permissible velocity is usually based upon the erosion resistance of a mature stand of vegetation. Newly seeded area or areas with immature vegetation are very susceptible to erosion damage. Therefore, temporary channel linings are typically recommended to prevent channel erosion until the vegetation is established. When used properly, temporary lining materials can greatly increase the success for achieving an adequate stand of vegetation. See Chapter 7 of VSWHB for more information on temporary lining materials.

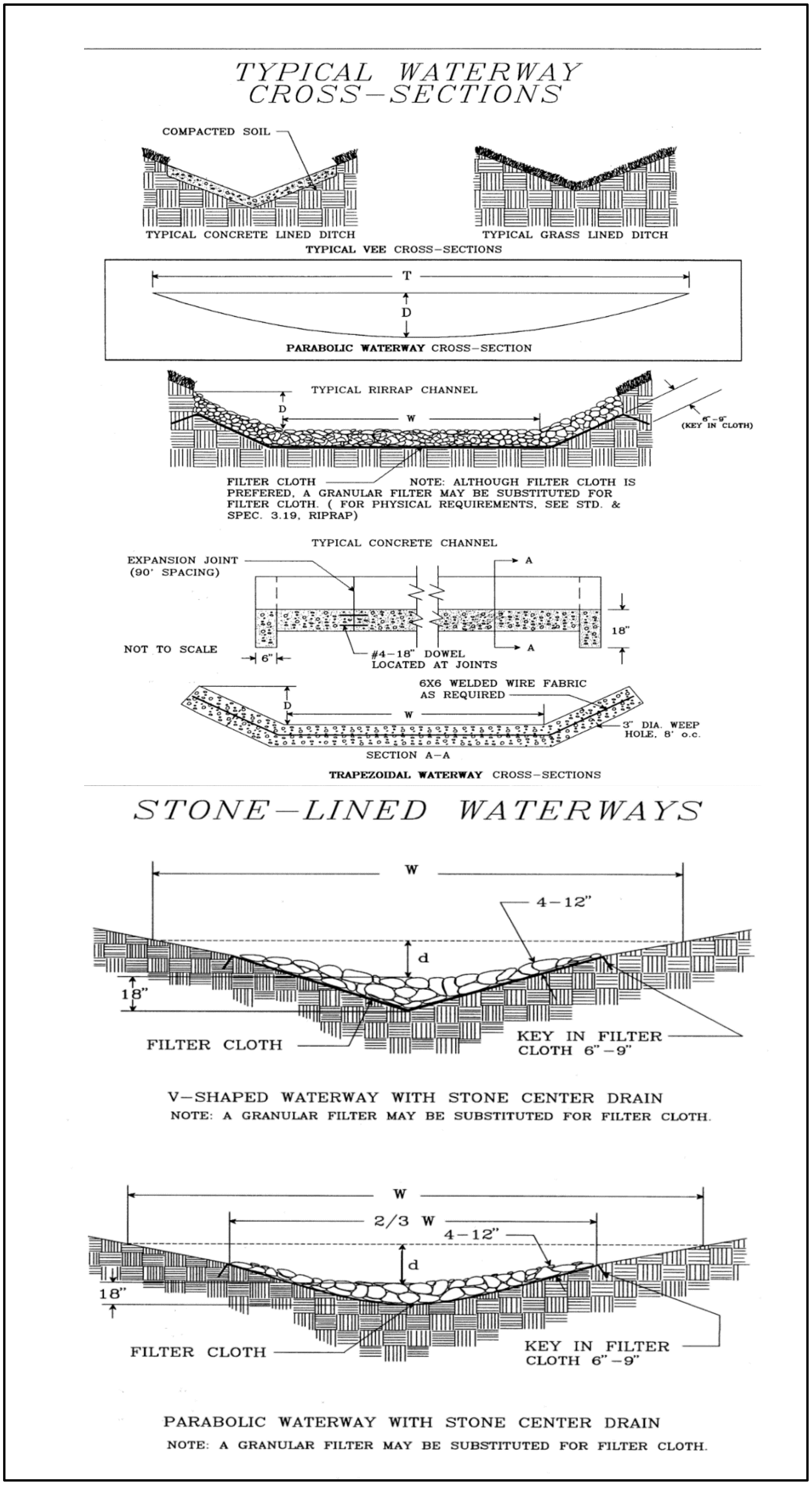


Figure 12-8: C-ECM-09 Stormwater Conveyance Channel Figures C-ECM-09-1 and -2

12e. Designing Channels

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) are known and can be used to find V.

Notes

Module 12 Problems

A plan reviewer needs experience manipulating the Tractive Force (Permissible Shear) Equation, Manning's Equation, and the Continuity Equation in order to become proficient at verifying the capacity and erodibility of ditch-lines 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 Module 9). The time of concentration, in turn, is used to calculate peak discharge using the rational and graphical peak discharge methods (Module 9 and Module 10, respectively).

Channel Geometry

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?

Rectangular Channel Area in square feet = Bottom Width in feet x Depth in feet

$$a = b \times d$$

a = ____________ feet x ____________ feet = ____________ square feet

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

Wetted Perimeter in feet = Bottom Width in feet + 2 x Depth in feet

$$p = b + 2d$$

p = ____________ feet + 2 x ____________ feet = ____________ feet

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

$$Hydraulic\ Radius\ in\ feet = \frac{Area\ in\ square\ feet}{Wetted\ Perimeter\ in\ feet}$$

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

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:

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

Area in square feet = Channel Side Slopes of Horizontal Distance x Channel Depth in 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?

$$Hydraulic\ Radius\ in\ feet = \frac{Area\ in\ square\ feet}{Wetted\ Perimeter\ in\ feet}$$

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

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)?

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

or

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

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

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

$$Hydraulic\ Radius\ in\ feet = \frac{Area\ in\ square\ feet}{Wetted\ Perimeter\ in\ feet}$$

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

r = ____________ square feet / ____________ feet = ____________ feet

Manning's Equation and Roughness Coefficients

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, and 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

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

or

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

Where:

V = Velocity (feet per second or 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 (erosion resistant soils), with Manning's Roughness Coefficient, n = 0.05; Slope, S = 0.06 feet/foot slope; and Hydraulic Radius, R = 1.5, what is the velocity of flow in this channel? Does it exceed the permissible velocity for Bermuda grass (erosion resistant soils)?

Manning's Equation

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

or

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

Where:
V = Velocity (feet per second or 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 VSWHB C-ECM-15, Table 15-2, Permissible Velocities for Grass-Lined Channels

S = s x 100

Where:
S = Channel Slope (%)

s = Channel Slope (feet/foot)

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

Permitted Velocity for Bermuda Grass (erosion resistant soils) at Slope _____________% = fps

Calculated velocity allowed? YES/NO

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 per second or fps)

A = Area (square feet)

Q = ______________ feet/second x ______________ square feet = _________ cubic feet/second