CHAPTER 6
OPEN CHANNEL DESIGN

GENERAL

Artificial stormwater channels are critical components of the stormwater management system. Three prime concerns govern their design: that they carry their design storm flows without overtopping, that they carry those flows without being excessively eroded, and that they are economically constructed and maintained. The consequence of failure to provide sufficient capacity is flooding. The consequences of excessive bank erosion are eventual undermining of facilities near the channel and abnormally high contributions of sediment to downstream channels and lakes.

The design of two frequently encountered channel types is treated here. One is the common trapezoidal channel, and the other is the triangular swale. The latter is a subset of the former. Triangular swales are usually used for smaller design discharges than trapezoidal channels.

MATHEMATICAL MODEL

The Manning equation is the model of choice for many design and analysis applications in which the channel is flowing under the influence of gravity. Its mathematical flexibility makes it a powerful tool in a wide variety of conditions. One should take care, however, to apply the equation in circumstances where its fundamental assumptions are satisfied.

The Manning equation is applicable where flow is steady and uniform. Steady flow means that discharge does not vary with time. Uniform flow means that velocity does not vary with distance at an instant of time. Although discharge does vary in a channel during the passage of a flood wave, during the time around the peak, the time of interest in channel design, flow is essentially steady. Uniform flow generally requires channel cross-sections to be the same along the channel length, and it requires a straight alignment. But it is reasonable to apply the Manning equation to most field cases where channel segments are practically prismatic and straight.

The Manning equation is well-suited to the task of determining the configuration of the cross section for the channel. Other models, such as water-surface profile computation, come into play after design when analyzing specific conditions of flow near obstructions, constrictions and other discontinuities.

DESIGN AND ANALYSIS PROCEDURES

Basic Concepts

The Manning equation can be stated as:

$$Q = \frac{1.486}{n} A R^{2/3} s^{1/2} \qquad (6\text{-}1)$$

in which

Q = Discharge (cfs).

n = Manning roughness coefficient (dimensionless), an experientially determined value which is a function of the nature of the channel lining.

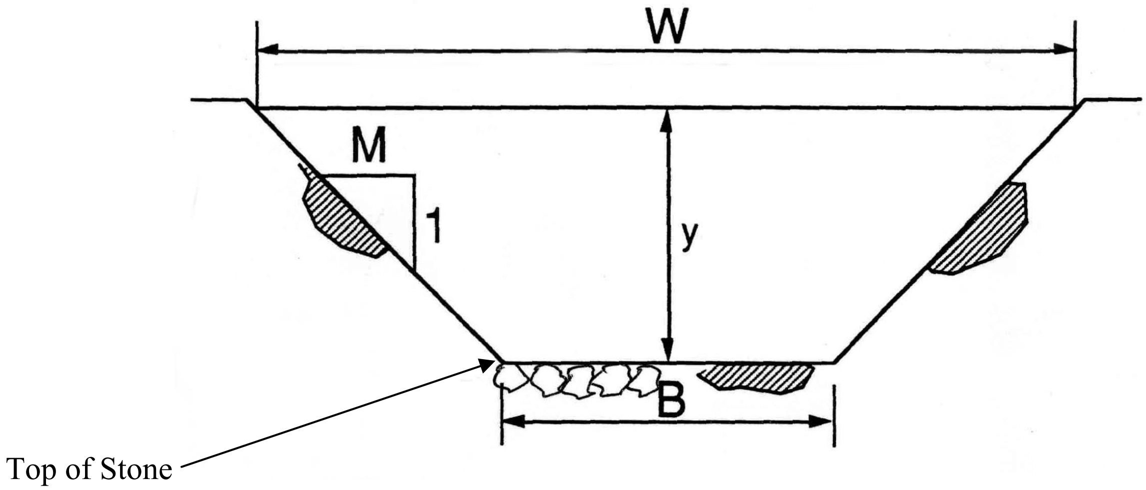
A = Cross-sectional area of flow (square feet), the area through which flow takes place.

R = Hydraulic radius (ft), found by dividing cross-sectional area, A (sq ft), by wetted perimeter, P (ft). Wetted perimeter is the distance along the perimeter of the cross section against which water is flowing. It does not include the free water surface.

s = Longitudinal slope of the water surface (ft fall/ft run). If flow is uniform, it is also the slope of the invert of the channel.

The constant, 1.486, is frequently rounded to 1.49, respecting that other parameters, most notably roughness, are rarely known to more than two significant figures. The constant has units associated with it. The value given here requires that the specified units be used for the values entered into the equation.

For the trapezoidal application, the following definition sketch indicates some of the variables:



In the sketch,

W = Top width of flow (ft).

B = Bottom width of the channel (ft)

y = Depth of flow (ft).

M = Side slope ratio (ft horizontal/ft vertical). (For a 2-to-1 side slope, the value of M is 2.)

Section Relationships

The following equations are derived geometrically, and the units of the variables are consistent with those given above:

$$A = By + My^2 \tag{6-2}$$

$$P = B + 2y\sqrt{1 + M^2} \tag{6-3}$$

$$W = B + 2My \tag{6-4}$$

$$R = \frac{A}{P} \tag{6-5}$$

The variable P represents wetted perimeter.

Four Main Procedures

Four main design tools are considered here. Each is an extension of the Manning equation and is subject to the same assumptions of the existence of steady, uniform flow. The tools are developed as the following procedures:

1. Best hydraulic section procedure.
2. Velocity-limited procedure.
3. Normal-depth procedure.
4. Depth-limited procedure.

Using these, singly or in combinations, one can quickly arrive at a cross section appropriate to the design objectives.

Best Hydraulic Section

The best hydraulic section is that cross section which simultaneously minimizes cross-sectional area and wetted perimeter. Minimizing cross-sectional area minimizes the quantity of excavation. Minimizing wetted perimeter minimizes the quantity of lining. These are the two principal cost sources in channel construction. Land taken by the channel is another cost source, and land quantity is not necessarily minimized in the best hydraulic section. But even when land is quite expensive, it does not influence greatly the economic choice of section dimensions. Thus, the best hydraulic section is likely to be the least expensive channel alternative, if it is otherwise satisfactory. If it will not work, it is usually because it is too deep for site conditions, or because flow will be too fast for the lining.

The best of all hydraulic sections is the semicircular cross section, but it is rare that it is practical. For trapezoidal cross sections, the best hydraulic section is half of a regular hexagon - a channel with side slopes too steep for many linings. But even for the usable side slopes, those flatter than 1/1, there is a certain combination of bottom width and depth that will minimize cross-sectional area and wetted perimeter, and thus qualify as the best hydraulic section for those conditions. The following procedure can be used to compute the bottom width (B) and the depth (y) of the best hydraulic section:

1. Select a candidate lining, and determine its Manning roughness coefficient, n.

2. Select a side slope, M, suitable for the soil and lining conditions.

3. From Exhibit 6-1 find the constants k and Cm for the side slope.

4. Find the depth, y, of the best hydraulic section from Equation 6-6.

5. Find the bottom width, B, of the best hydraulic section from Equation 6-7.

6. Check the depth, y, against profile constraints.

7. Compute the average cross-sectional velocity, V = Q/A, and check against the lining velocity limit.

8. If these values of B and y are used with the other data in the Manning equation, it will yield the design discharge, Q.

The depth, y, and bottom width, B, of the best hydraulic section can be found from Equations 6-6 and 6-7, and Exhibit 6-1.

$$y = Cm\left[\frac{Qn}{\sqrt{s}}\right]^{3/8} \qquad (6\text{-}6)$$

$$B = ky \qquad (6\text{-}7)$$

Note that the depth and bottom width computed in Equations 6-6 and 6-7 are a "matched pair." Equation 6-6 is no good for computing the depth of flow in a channel for which the bottom width is known. Use the Normal Depth procedure for that.

Velocity-Limited Procedure

Frequently, in the design of trapezoidal channels, the velocity expected for the best hydraulic section is too great for the lining of interest. The following procedure will avoid a laborious trial-and-error exercise:

1. Ensure that the assigned velocity, V_a, is less than the velocity of flow computed for the best hydraulic section (the channel will not flow any faster).

2. Compute the required cross-sectional area:

$$A_x = \frac{Q}{V_a} \qquad (6\text{-}8)$$

where

A_x = Required cross-sectional area (sq ft)
Q = Design flow (cfs).
V_a = Assigned (desired) velocity (ft/sec)

3. Compute working constants:

$$W_1 = M - 2\sqrt{1 + M^2} \qquad (6\text{-}9)$$

(W_1 is always negative.)

$$W_2 = \frac{A_x}{\left[\frac{V_a\, n}{1.49\sqrt{s}}\right]^{3/2}} \qquad (6\text{-}10)$$

4. Compute the depth of flow:

$$y = \frac{-W_2 + \sqrt{W_2^2 + 4W_1 A_x}}{2W_1} \qquad (6\text{-}11)$$

5. Compute the bottom width:

$$B = \frac{A_x}{y} - My \qquad (6\text{-}12)$$

6. If these values of B and y are used with the other data in the Manning equation, it will yield the design discharge, Q; and, if velocity is computed, it will equal V_a.

The Velocity-Limited procedure frequently produces a channel that is unrealistically wide and shallow. This will happen if the assigned velocity, V_a, is significantly slower than the best-hydraulic-section velocity. It is usually better to go to a more robust lining than to put in a very wide channel.

Normal-Depth Procedure

The problem of finding the normal depth of flow in a trapezoidal channel is very frequently encountered. It is necessarily a trial-and-error procedure. To find normal depth is to find the depth of flow, y, that satisfies the Manning equation. Usually one is asked for the expected depth when a certain flow occurs, given the dimensions of the channel, including bottom width.

An efficient manual procedure for finding normal depth follows.

Rearrange the Manning Equation as:

$$A\,R^{2/3} = \frac{Qn}{1.49\sqrt{s}} \qquad (6\text{-}13)$$

In this form, the right-hand side contains knowns, and the left- hand side contains unknowns. When the values of B and y, and thus A and R, are chosen correctly, the left-hand side will equal the right-hand side and Manning is satisfied. So, think of the right-hand side as a required quantity, Z_{req}. It can be computed as a single value at the beginning of the problem:

$$Z_{req} = \frac{Q\,n}{1.49\sqrt{s}} \qquad (6\text{-}14)$$

Think of the left-hand side as the quantity available in a given section, Z_{av}:

$$Z_{av} = AR^{2/3}$$

Now, select y such that Z_{av} is tolerably close to Z_{req} , and that y is the depth at which the channel will flow.

Depth-Limited Procedure

The depth-limited procedure is quite useful for cases where channel depth is limited by profile constraints. The procedure can be executed precisely parallel to the normal-depth procedure detailed above. One decides on the depth at which the channel should flow under the given conditions. The bottom width is computed as the output.

Triangular Swales

Triangular swales may be treated as trapezoidal channels with bottom width, B, equal to zero. The four analytical tools described for trapezoidal channels apply. It is true, however, that the absence of a bottom width makes it unnecessary to resort to trial-and-error solutions in many cases. One can substitute into the Manning equation directly and find solutions algebraically.

When a triangular swale is the economical solution, a best-hydraulic-section analysis will point to it. Bottom width, B, will compute to a trivially small value. Note that the bottom width can never be exactly zero, because depth, y, cannot be zero, and Equation 6-7 will always yield a non-zero value for B. Triangular swales will usually be the solution of choice when side slopes are flat, say 4/1 or flatter.

Grass-lined triangular swales are frequently used in open-area drainage, such as roadway medians, interchanges, open space in developments of multi-family dwellings, and along streets not constructed with curb and gutter. In these applications, the capacity of the grass-lined swale is normally limited to the discharge at which flow approaches erosive velocity. Two mathematical models can be combined to compute an allowable drainage area for a given point along a channel. If the actual drainage area exceeds the allowable, one would expect the channel to erode. Equating the Rational formula and the Manning equation through the discharge Q, and solving for the allowable drainage area in terms of other parameters set in the design process, one obtains:

$$Ad = \frac{1.21\, V_a^4 \,(1 + M^2)}{CIM} \left[\frac{n}{\sqrt{s}}\right]^3 \qquad (6\text{-}16)$$

in which

- Ad = Allowable drainage area (ac) for the point of interest along the channel.
- I = Applicable rainfall intensity (in/hr) for the storm of interest (usually the 5-min. storm of an appropriate return period.
- C = Rational runoff coefficient (dimensionless), composited for the drainage area.
- n = Manning roughness coefficient (dimensionless) for the channel lining.
- s = Longitudinal channel slope (dimensionless) at the point of interest along the channel.
- V_a = Allowable velocity of flow (ft/sec) for the channel lining.
- M = Horizontal component of side slope (for 2/1, M = 2)

Once these parameters have been set for the point of interest, for detailing purposes, the following can be computed <u>for conditions of full allowable flow:</u>

The allowable discharge is:

$$Q=CIAd=V_aMy^2 \qquad (6\text{-}17)$$

The depth of flow at allowable discharge is:

$$y = \left[\frac{C\,I\,Ad}{V_a M}\right]^{1/2} \quad (6\text{-}18)$$

The top width (for setting the required width of lining at allowable flow) is:

$$W=2My \quad (6\text{-}19)$$

The equations are most useful in a spreadsheet or in a program for a programmable calculator. Their best use is to move along a channel on the site plan, selecting points of interest and comparing the allowable to the actual drainage area. By trial and error, points may be found below which the channel would be overloaded. At such points, an inlet may be placed to relieve the load on the channel, or the channel may be lined as a concrete swale below that point.

The equations also may be used to determine the extent and width of lining material to protect the channel against erosion just after construction until grass is established.

Reference Data for Channels

Typically, experiential information is needed to set the Manning roughness coefficient and to set limits on velocity of flow to preclude excessive bank erosion. The author has collected some defensible values for Manning roughness coefficients in Exhibit 6-2. Suggested values for allowable velocities for various linings appear in Exhibit 6-3.

Practical Considerations

The following are suggestions from a number of practitioners:

1. Fine materials in the soil underlying a stone lining tend to migrate through the stone into the channel during high-flow events. A stone filter blanket or filter fabric placed between the stone lining and the bank material shall be utililized.

2. The depth of stone lining should be two to three stone diameters.

3. In some cases, designers line the banks, but not the bed. The bed is subjected to greater erosive stresses than the bank. If the bed is not lined, the designer should ensure that the bed material is sufficiently robust.

4. Give special consideration to points of heaviest stress. These are the center of the bottom, on the bank about one fifth to one third of the depth up from the bottom, and along the outside of bends.

5. In the design process, account for the projected maintenance policy for the channel lining. If weeds will be allowed to grow on the banks, they must be considered in setting the section dimensions.

Best Hydraulic Section Coefficients

M	Cm	k	Comment
0 /1	0.790	2.000	Vertical sides
0.5 /1	0.833	1.236	
0.577 /1	0.833	1.155	60-degree sides
1 /1	0.817	0.828	45-degree sides
1.5 /1	0.775	0.606	
2 /1	0.729	0.472	
2.5 /1	0.688	0.385	
3 /1	0.653	0.325	Steepest to mow
3.5 /1	0.622	0.280	
4 /1	0.595	0.246	
5 /1	0.552	0.198	
6 /1	0.518	0.166	
7 /1	0.490	0.142	
8 /1	0.467	0.125	
9 /1	0.447	0.111	
10 /1	0.430	0.100	
11 /1	0.415	0.091	
12 /1	0.402	0.083	

EXHIBIT 6-1

Abbreviated Table of Values of Manning Roughness Coefficients.

Description of Lining	n
Reinforced concrete pipe	0.013
Corrugated metal pipe	0.024
Concrete, trowelled finish	0.013
Concrete, float finish	0.015
Street gutter or paved channel	0.015
Earth, straight and uniform	0.022
Grass-lined swales	0.030
Unmaintained brushy channel	0.080
Stone-lined channel (4-inch)	0.028
Stone-lined channel (6-in)	0.030
Stone-lined channel (9-in)	0.032
Stone-lined channel (12-in)	0.034
Stone-lined channel (15-in)	0.035
Stone-lined channel (18-in)	0.036

EXHIBIT 6-2

Suggested Maximum Velocities for Various Channel Linings

Description	Allowable Velocity (ft/sec)
Native linings	
Fine sand	2.5
Sandy loam	2.5
Silt loam	3.0
Ordinary firm loam	3.5
Fine gravel	5.0
Stiff clay	5.0
Grass	
Uncertain maintenance	4.0
Good cover, proper maintenance	5.0

Quarry Stone

Equivalent Spherical Diameter (inches)	Allowable Velocity (ft/sec) for stated sideslope					
	1/1	1.5/1	2/1	3/1	4/1	12/1
6	6.0	7.1	7.7	8.0	8.4	9.0
9	7.2	8.9	9.4	9.8	10.2	10.8
12	8.5	10.2	10.7	11.2	11.8	12.5
15	9.5	11.5	12.0	12.7	13.3	14.0
18	10.7	12.6	13.2	14.0	14.4	15.3
24	12.5	14.3	15.1	16.2	16.7	17.6
30	14.0	15.9	17.0	18.2	18.7	19.7
36	15.4	17.4	18.7	20.0	20.5	21.5

EXHIBIT 6-3