CHAPTER 3

OPEN CHANNEL HYDRAULICS

3.1 OVERVIEW

3.1.1 Introduction

This chapter emphasizes procedures for performing uniform calculations that aid in the selection or evaluation of appropriate channel linings, depths, and grades for natural or man-made channels. Allowable velocities are provided, along with procedures for evaluating channel capacity using Manning's equation. For information on roadside ditch requirements see Chapter 4.

3.1.2 Channel Linings

The three main classifications of open channel linings are vegetative, flexible and rigid. Vegetative linings include grass with mulch, sod, and lapped sod. Rock riprap is a flexible lining, while rigid linings are generally concrete.

3.1.2.1 Vegetative

Vegetation is the most desirable lining for an artificial channel. It stabilizes the channel body, consolidates the soil mass of the bed, inhibits erosion on the channel surface, and controls the movement of soil particles along the channel bottom. Conditions under which vegetation may not be acceptable; however, include but are not limited to:

1. Flow conditions in excess of the maximum shear stress for bare soils;
2. Standing or continuous flowing water;
3. Lack of regular maintenance necessary to prevent domination by taller vegetation;
4. Lack of nutrients and inadequate topsoil;
5. Excessive shade; or
6. Excessive velocities

Proper seeding, mulching, and soil preparation are required during construction to ensure establishment of a healthy stand of grass. Soil testing may be performed and the results evaluated by an agronomist to determine soil treatment requirements for pH, nitrogen, phosphorus, potassium, and other factors. In many cases, temporary erosion control measures are required to provide time for the seeding to establish a viable vegetative lining.

Sodding should be staggered, to avoid continuous seams in the direction of flow. Lapped or shingle sod should be staggered and overlapped by approximately 25 percent. Staked sod is usually only necessary for use on steeper slopes to prevent sliding.

3.1.2.2 Flexible

Rock riprap including rubble is the most common type of flexible lining. It presents a rough surface that can dissipate energy and mitigate increases in erosive velocity. These linings are usually less expensive than rigid linings and have self-healing qualities that reduce maintenance. They typically require use of filter fabric and allow the infiltration and exfiltration of water. The growth of grass and weeds through the lining may present maintenance problems. The use of flexible lining may be restricted where space is limited, since the introduction of linings with higher roughness values generally results in the need for greater channel capacity.

3.1.2.3 Rigid

Rigid linings are generally constructed of concrete and used where smoothness offers a higher capacity for a given cross-sectional area. Higher velocities, however, create the potential for scour at channel lining transitions. A rigid lining can be damaged by flow undercutting the lining, channel headcutting, or the buildup of hydrostatic pressure behind the rigid surfaces. When properly designed, rigid linings may be appropriate where the channel width is restricted. Filter fabric may be required to prevent soil loss through pavement cracks.

Under continuous base flow conditions when a vegetative lining alone would be appropriate, a small concrete pilot channel could be used to convey the continuous low flows. Vegetation could then be maintained for conveying larger flows.

3.2 DESIGN CRITERIA

3.2.1 General Criteria

The following criteria shall be used for open channel design:

1. Channel side slopes shall be stable throughout the entire length and slope shall be no steeper than 2:1.
2. Superelevation of the water surface at horizontal curves shall be accounted for by increased freeboard.
3. A minimum freeboard of 6” must be provided in the 10-year design storm.
4. Transition from closed systems to channel sections (or between transitioning channel sections) shall be smooth and gradual, with a minimum of 5:1 taper.
5. Low flow sections shall be considered in the design of channels with large cross-sections (Q > 100 cfs). Some channel designs will be required to have increased freeboard (see North Carolina Erosion and Sediment Control Planning and Design Manual, Section 8.05.21).

3.2.2 Return Period

Open channel drainage systems shall be designed to convey a 10-year design storm. The peak flow rate for the 100-year storm shall be computed at appropriate points within the drainage system to determine if a 100 + 1 flood study is required as described in section 3.2.3.

Sediment transport requirements must be considered for conditions of flow below the design frequency. A low flow channel component within a larger channel can reduce maintenance by improving sediment transport in the channel.

3.2.3 100+1 Flood Analysis

All streams in the City of Charlotte and Mecklenburg County which drain more than one square mile (640 acres) are regulated by Floodplain Ordinances, which restrict development in those flood plains. However, storm water conveyances that drain less than one square mile will also flood and require regulation as well. This regulation is known as the 100+1 flood analysis.

The following criteria will be used to determine how and when the 100+1 flood analysis will be used.

1. The 100+1 analysis will be required for all portions of the drainage system which are expected to carry 50 cfs or more for the 100-year storm.

2. The 100-year storm water surface elevations should be calculated using a method acceptable to the City/County Engineering Department, as further described in Section 3.6.
3. The peak flow rate used in the 100+1 analysis shall be based on an assumption of full build out of the contributing tributary drainage area. The assumption of full build out shall be defined as either full development per the current zoning of the property, the existing land use, or adopted area land use plans, whichever generates the higher runoff rate.
4. For drainage systems within development projects subject to the Subdivision Ordinance, the 100+1 elevation and flood limits shall be shown on the recorded maps associated with the subdivision as further described in the Subdivision Ordinance.
5. For drainage systems within development projects not subject to the Subdivision Ordinance, the City/County Engineering Department may require that the 100+1 elevation be shown on a recorded map if the engineering analysis indicates that one of the following conditions is present:
   - The 100+1 line would exceed the set-back limits.
   - The estimated runoff or proposed modifications to a storm water conveyance would create a hazard for the adjacent properties or residents.
   - The flood limits would be of such magnitude that adjacent property owners should be informed of these limits.

3.2.4 Velocity Limitations

The design of open channels should be consistent with the velocity limitations for the selected channel lining. For design information see section 3.4 Open Channel Design.

3.3 MANNING'S N VALUES

3.3.1 General Considerations

The Manning's *n* value is an important variable in open channel flow computations. Variation in this variable can significantly affect discharge, depth and velocity estimates. Since Manning's *n* values depend on many different physical characteristics of natural and man-made channels, care and good engineering judgment must be exercised in the selection process.

3.3.2 Selection

The following general factors should be considered when selecting the value of Manning's *n*:

1. The physical roughness of the bottom and sides of the channel. Fine particle soils on smooth, uniform surfaces result in relatively low values of *n*. Coarse materials such as gravel or boulders, and pronounced surface irregularity cause higher values of *n*.
2. The value of *n* depends on the height, density, and type of vegetation and how the vegetation affects the flow through the channel reach.
3. Channel dimension variations, such as abrupt changes in channel cross sections or alternating small and large sections, will require somewhat larger *n* values than normal. These variations in channel cross section become particularly important if they cause the flow to meander from side to side within the channel.
4. A significant increase in the value of *n* is possible if severe meandering occurs in the alignment of a channel. Meandering becomes particularly important when frequent changes in the direction of curvature occur with relatively small radii of curvature.

5. Active channel erosion or sedimentation (degradation and aggradation) will tend to increase the value of *n*, since these processes may cause variations in the shape of a channel. The potential for future erosion or sedimentation in the channel must also be considered.
6. Obstructions such as log jams or deposits of debris will increase the value of *n*. The level of this increase will depend on the number, type and size of obstructions.
7. To be conservative, it is better to use a higher resistance for capacity calculations and a lower resistance for stability calculations.
8. Proper assessment of natural channel *n* values requires field observations and experience. Special attention is required in the field to identify flood plain vegetation and evaluate possible variations in roughness with depth of flow.

All of these factors should be evaluated with respect to type of channel, degree of maintenance, seasonal requirements, and other considerations as a basis for determining appropriate design *n* values. The probable condition of the channel when the design event is anticipated should be considered. Values representative of a newly constructed channel are rarely appropriate as a basis for design capacity calculations.

3.3.3 Manning's *n* Values

Recommended Manning's *n* values for natural channels are given in Table 3-1 and recommended Manning's *n* values for artificial channels are given in Table 3-2.

Table 3-1
Recommended Manning's *n* Values for Natural Channels

Type of channel and description	Minimum	Normal	Maximum
NATURAL LININGS			
Minor Streams (top width at flood stage < 100 ft)			
a. Streams on plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4, but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy deep pools	0.050	0.070	0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2. Bottom: cobbles with large boulders	0.040	0.050	0.070
Flood Plains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crop	0.025	0.035	0.045
3. Mature field crop	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense willows, summer, straight	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160

Abridged from Chow, V.T., ed. 1959, Open-Channel Hydraulics

Table 3-2
Recommended Manning's *n* Values for Artificial Channels

RIP RAP	***n* (depth of flow >=2')**
Class B stone	0.037
Class 1 rip rap	0.040
Class 2 rip rap	0.045

Note: See Table 3-7 for temporary lining materials such as straw matting. If using values other than ones listed above or in Table 3-7, please provide documentation.

3.4 OPEN CHANNEL DESIGN

3.4.1 Overview

This section addresses the design of stable conveyance channels using vegetative and flexible linings. A stable channel is defined as a channel which is non-silting and non-scouring. To minimize silting in the channel, flow velocities should remain constant or increase slightly throughout the channel length.

Vegetative and flexible channel linings are generally preferred to rigid linings from an erosion control perspective because they conform to changes in channel shape without failure and are less susceptible to damage from frost heaving, soil swelling and shrinking, and excessive soil pore water pressure from lack of drainage. Vegetative and flexible linings also are generally less expensive to construct, and generally are more natural in appearance. On the other hand, vegetative and flexible linings generally have higher roughness coefficients and may require a larger cross section for the same discharge.

3.4.2 Design of Stable Channels

The minimum design criteria for conveyance channels require that two primary conditions be satisfied: the channel system must have capacity for the peak flow expected from the 10-year storm and the channel lining must be resistant to erosion for the design velocity. In some cases for intermittent and perennial systems, out-of-bank flow may be considered a functional part of the channel system. In those cases, flow capacities and design velocities should be considered separately for out-of-bank flows and channel flows. Design methodology for these larger more natural stream systems is not included in this manual.

Both the capacity of the channel and the velocity of flow are functions of the channel lining, cross-sectional area and slope. The channel system must carry the design flow with adequate freeboard, fit site conditions and be stable.

The following procedures are needed for designing stable channels: (1) the permissible velocity procedure (for permanent vegetative linings); and (2) the tractive force procedure (for temporary lining materials or riprap linings). Under the permissible velocity procedure, the channel is considered stable if the design mean velocity is lower than the maximum permissible velocity. Under the tractive force procedure, erosive stress evaluated at the boundary between flowing water and lining materials must be less than the minimum unit tractive force that will cause serious erosion of material from a level channel bed.

3.4.3 Permissible Velocity

The permissible velocity procedure uses two equations to calculate flow:

Manning's equation,

$$\mathbf{V = \frac{1.49\,R^{2/3}\,S^{1/2}}{n}} \qquad \textbf{(3.1)}$$

Where: V = average velocity in the channel (ft/sec)

n = Manning's roughness coefficient, based upon the lining of the channel

R = hydraulic radius, wetted cross-sectional area/wetted perimeter (ft)

S = slope of the channel (ft/ft)

And the continuity equation,

$$\mathbf{Q = AV} \qquad \textbf{(3.2)}$$

Where: Q = flow in the channel (cfs)

A = cross-sectional area of flow within the channel (square feet - ft^2)

V = average velocity in the channel (ft/sec)

Manning's equation and the continuity equation are used together to determine channel capacity and flow velocity.

3.4.4 Selecting Permanent Channel Lining

The design of concrete and similar rigid linings is generally not restricted by flow velocities. However, vegetative and flexible channel linings do have maximum permissible flow velocities beyond which they are susceptible to erosion. The designer should select the type of liner that best fits site conditions.

Table 3-3 lists maximum permissible velocities for established grass linings and soil conditions. Before grass is established, permissible velocity is determined by the choice of temporary liner. Permissible velocities for riprap linings are higher than for grass and depend on the stone size selected.

Table 3-3
Maximum Allowable Design Velocities[1]
for Vegetated Channels

Typical Channel Slope Application	Soil Characteristics[2]	Grass Lining	Permissible Velocity[3] for Established Grass Lining (ft/sec)
0-5%	Easily Erodible	Bermudagrass	5.0
	Non-plastic	Tall fescue	4.5
	(Sands & Silts)	Bahiagrass	4.5
		Kentucky bluegrass	4.5
		Grass-legume mixture	3.5
	Erosion Resistant	Bermudagrass	6.0
	Plastic	Tall fescue	5.5
	(Clay mixes)	Bahiagrass	5.5
		Kentucky bluegrass	5.5
		Grass-legume mixture	4.5
5-10%	Easily Erodible	Bermudagrass	4.5
	Non-plastic	Tall fescue	4.0
	(Sands & Silts)	Bahiagrass	4.0
		Kentucky bluegrass	4.0
		Grass-legume mixture	3.0
	Erosion Resistant	Bermudagrass	5.5
	Plastic	Tall fescue	5.0
	(Clay mixes)	Bahiagrass	5.0
		Kentucky bluegrass	5.0
		Grass-legume mixture	3.5
>10%	Easily Erodible	Bermudagrass	3.5
	Non-plastic	Tall fescue	2.5
	(Sands & Silts)	Bahiagrass	2.5
		Kentucky bluegrass	2.5
	Erosion Resistant	Bermudagrass	4.5
	Plastic	Tall fescue	3.5
	(Clay mixes)	Bahiagrass	3.5
		Kentucky bluegrass	3.5

Source: USDA-SCS Modified

NOTE:
1 Permissible Velocity based on 10-year storm peak runoff
2 Soil erodibility based on resistance to soil movement from concentrated flowing water (soil types are based on NRCS soils data).
3 Before grass is established, permissible velocity is determined by the type of temporary liner used.

3.4.5 Tractive Force

This procedure is for uniform flow in channels and is ***not*** to be used for design of deenergizing devices and may not be valid for larger channels.

To calculate the required size of an open channel, assume the design flow is uniform and does not vary with time. Since actual flow conditions change through the length of a channel, subdivide the channel into design reaches as appropriate.

The permissible shear stress, T_d, is the force required to initiate movement of the lining material. Permissible shear stress for the liner is not related to the erodibility of the underlying soil. However, if the lining is eroded or broken, the bed material will be exposed to the erosive force of the flow.

Shear stress, T, at normal depth is computed for the lining by the following equation:

$$\mathbf{T = \omega ds} \qquad \textbf{(3.3)}$$

$$T_d > T$$

Where: T = computated shear stress (in lb/ft^2)

T_d = Permissible shear stress (Table 3-8)

ω = unit weight of water, 62.4 lb/ft^3

d = flow depth (ft)

s = channel gradient (ft/ft)

If the permissible shear stress, T_d, is greater than the computed shear stress, the riprap or temporary lining is considered acceptable. If a lining is unacceptable, select a lining with a higher permissible shear stress and repeat the calculations for normal depth and shear stress. In some cases it may be necessary to alter channel dimensions to reduce the shear stress.

Computing tractive force around a channel bend requires special considerations because the change in flow direction imposes higher shear stress on the channel bottom and banks. The maximum shear stress in a bend, T_b, is given by the following equation:

$$\mathbf{T_b = KbT} \qquad \textbf{(3.4)}$$

Where: T_b = bend shear stress (lb/ft^2)

K_b = bend factor

T = computed stress for straight channel (lb/ft^2)

The value of K_b is related to the radius of curvature of the channel at its centerline, R_c, and the bottom width of the channel, B, Figure 3- 2. The length of channel requiring protection downstream from a bend, L_p, is a function of the roughness of the lining material and the hydraulic radius as shown in Figure 3-3.

3.4.6 Design Procedure Using Permissible Velocity and Tractive Force Procedures

The following is a step-by-step procedure for designing a runoff conveyance channel using Manning’s equation and the continuity equation:

Step 1. Determine the required flow capacity, Q, by estimating peak runoff rate for the design storm.

Step 2. Determine the slope and select channel geometry and lining.

Step 3. Determine the permissible velocity for the lining selected, or the desired velocity, if paved (see Table 3-3).

Step 4. Make an initial estimate of channel size - divide the required Q by the permissible velocity to reach a “first try” estimate of channel flow area. Then select a geometry, depth, and top width to fit site conditions.

Step 5. Calculate the hydraulic radius, R, from channel geometry (Figure D-1, Appendix 3D).

Step 6. Determine roughness coefficient *n*.

Structural Linings - see Table 3-4.

Grass Lining:

a. Determine retardance class for vegetation from Table 3-5. To meet stability requirement, use retardance for newly mowed condition (generally C or D). To determine channel capacity, use at least one retardance class higher.

b. Determine *n* from Figure 3-1.

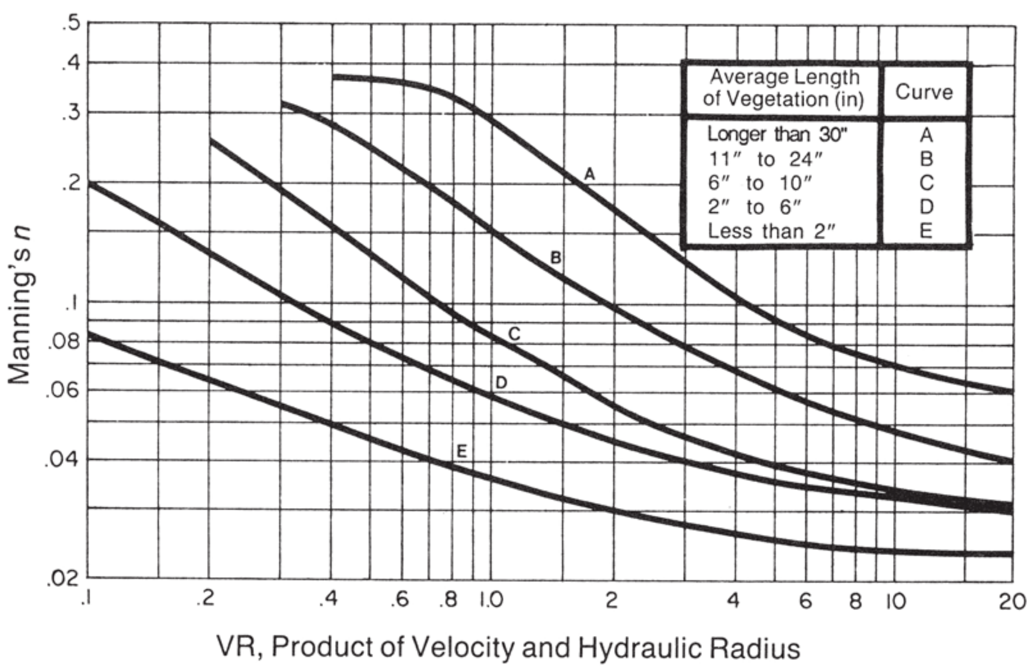


Figure 3-1 Manning’s *n* Related to Velocity, Hydraulic Radius, and Vegetal Retardance
Source: www.dlr.enr.state.nc.us/images/Sediment_design_manual_June2006/ChapterEight_20070419.PDF, page 599

Step 7. Calculate the actual channel velocity, V, using Manning’s equation (3.1) and calculate channel capacity, Q, using the continuity equation (3.2).

Step 8. Check results against permissible velocity and required design capacity to determine if design is acceptable.

Step 9. If design is not acceptable, alter channel dimensions as appropriate. For trapezoidal channels, this adjustment is usually made by changing the bottom width.

Step 10. For grass-lined channels once the appropriate channel dimensions have been selected for low retardance conditions, repeat steps 6 through 8 using a higher retardance class, corresponding to tall grass. This step is to verify that once the channel is fully established it is still designed appropriately. Adjust capacity of the channel by varying depth where site conditions permit.

> NOTE 1: If design velocity is greater than 2.0 ft/sec., a temporary lining may be required to stabilize the channel until vegetation is established. The temporary liner may be designed for peak flow from the 2-year storm. If a channel requires a temporary lining, the designer should analyze shear stresses in the channel to select the liner that provides protection and promotes establishment of vegetation. For the design of temporary liners, use the tractive force procedure.

Step 11. Check outlet for carrying capacity and stability. If discharge velocities exceed allowable velocities (Table 3-6) for the receiving stream, an outlet protection structure will be required. See Chapter 7 Energy Dissipation for design requirements.

Step 12. Add required 6-inch freeboard to design depth of channel cross section.

Step 13. Check to see if a temporary liner is necessary, as referenced in Note -1 of Step-10 above.

Step 14. Select a temporary liner material suitable for site conditions and application. Determine roughness coefficient from manufacturer's specifications or Table 3-7. Calculate the normal flow depth using Manning's equation (3.1). Check to see that calculated depth is consistent with that assumed for selection of Manning's roughness coefficient. The coefficient of roughness generally decreases with increasing flow depth.

Step 15. Calculate shear stress at normal depth.

Step 16. Compare computed shear stress with the permissible shear stress for the liner.

Step 17. If computed shear is greater than permissible shear, adjust channel dimensions to reduce shear, or select a more resistant lining and repeat steps 13 through 17.

Table 3-4
Manning's *n* Values for Structural Channel Linings

Channel Lining	Recommended *n* values
Asphaltic concrete, machine placed	0.014
Asphalt, exposed prefabricated	0.015
Concrete	0.015
Metal, corrugated	0.024
Plastic	0.013
Shotcrete	0.017
Gabion	0.030
Earth	0.020

Source: American Society of Civil Engineers (modified)

Table 3-5
Retardance Classification for Vegetal Covers

Retardance	Cover	Condition
A	Reed canarygrass	Excellent stand, tall (average 36”)
	Weeping lovegrass	Excellent stand, tall (average 30”)
B	Tall fescue	Good stand, uncut, (average 18”)
	Bermudagrass	Good stand, tall (average 12”)
	Grass-legume mixture (tall fescue,redfescue, sericealespedeza)	Good stand, uncut
	Grass mixture (timothy, smooth bromegrass ororchardgrass)	Good stand, uncut (average 20”)
	Sericea lespedeza	Good stand, not woody, tall (average 19”)
	Reed canarygrass	Good stand, cut, (average 12-15”)
	Alfalfa	Good stand, uncut (average 11”)
C	Tall fescue	Good stand (8-12”)
	Bermudagrass	Good stand, cut (average 6”)
	Bahiagrass	Good stand, uncut (6-8”)
	Grass-legume mixture--summer (orchardgrass,redtop and annuallespedeza)	Good stand, uncut (6-8”)
	Centipedegrass	Very dense cover (average 6”)
	Kentucky bluegrass	Good stand, headed (6-12”)
	Redtop	Good stand, uncut (15-20”)
D	Tall fescue	Good stand, cut (3-4”)
	Bermudagrass	Good stand, cut (2.5”)
	Bahiagrass	Good stand, cut (3-4”)
	Grass-legume mixture--fall-spring (orchardgrass,redtop, andannual lespedeza)	Good stand, uncut (4-5”)
	Red fescue	Good stand, uncut (12-18”)
	Centipedegrass	Good stand, cut (3-4”)
	Kentucky bluegrass	Good stand, cut (3-4”)
E	Bermudagrass	Good stand, cut (1.5”)
	Bermudagrass	Burned stubble

Modified from: USDA-SCS, 1969. Engineering Field Manual

Table 3-6
Maximum Velocities for Unprotected
Soils in Existing Channels

Materials	**Maximum Permissible Velocities (ft/s)**
Fine Sand (noncolloidal)	2.5
Sand Loam (noncolloidal)	2.5
Silt Loam (noncolloidal)	3.0
Ordinary Firm Loam	3.5
Fine Gravel	5.0
Stiff Clay (very colloidal)	5.0
Graded, Loam to Cobbles (noncolloidal)	5.0
Graded, Silt to Cobbles (colloidal)	5.5
Alluvial Silts (noncolloidal)	3.5
Alluvial Silts (colloidal)	5.0
Coarse Gravel (noncolloidal)	6.0
Cobbles and Shingles	5.5

3.4.7 Example Problem

Step 1: Design Q_{10} = 16.6 cfs
Q_2 = 11.9 cfs

Step 2: Proposed channel grade = 2%
Proposed vegetation: Tall fescue
Soil: Creedmoor (easily erodible)
Trapezoidal channel dimensions:
designing for low retardance (class D) condition
designing to meet V_p

Step 3: Permissible velocity, V_p = 4.5 ft/s (Table 3-3)

Step 4: Make an initial estimate of channel size
A = Q/V, 16.6 cfs/4.5 ft/sec = 3.7 ft^2
Try bottom width (b) = 3.0 ft w/side slopes of 3:1 (M= 3)

Step 5: $R = A / P$
$A = by + My^2$
$P = b + 2y (M^2 + 1)^{1/2}$

Steps 6 - 8: An iterative solution using Figure 3-1 to relate flow depth to Manning's *n* proceeds as follows. Retardance class: "D" cut (Table 3-5). Manning's equation (3.1) is used to check velocities and Continuity equation (3.2) is used to calculate flow. Check results against permissible velocity and required design capacity to determine if design is acceptable. Iterate as necessary.

y (ft)	A (ft^2)	R (ft)	**n*	V (ft/s)	Q (cfs)	Comments
0.8	4.32	0.54	0.043	3.25	14.0	$V< V_p$ ok $Q< Q_{10}$ too small
0.9	5.13	0.59	0.042	3.53	18.1	$V< V_p$ ok $Q> Q_{10}$ ok

Note: From Fig. 3-1 use Retardance Class D line and permissible velocity,V_p x calculated R (4.5x0.54 = 2.43) to get corresponding **n* = 0.043

Step 9: Not needed in this example since original bottom width guess worked.

Step 10: Now design for high retardance (Class B): Repeat steps 6 - 8.
For the ease of construction and maintenance, try y = 1.5 feet and trial velocity V_t = 3 ft/s

y (ft)	A (ft^2)	R (ft)	V_t (ft/s)	**n*	V(ft/s)	Q (cfs)	Comments
1.5	11.25	0.9	3	0.08	2.5	28	reduce V_t ,try 2
			2	0.11	1.8	20	reduce V_t ,try 1.6
			1.6	0.12	1.6	18	check V_t = 1.5
			1.5	0.13	1.5	17	$Q> Q_{10}$ ok

Step 11: Energy dissipation not needed in this example.

Step 12: After adding 6 inches of freeboard – required channel depth is 2 feet.
Channel Summary: Trapezoidal shape, M = 3, b = 3 ft, y = 2 ft, grade = 2%

Note: In the example problem, the Manning's *n* is first chosen based on a permissible velocity and not a design velocity criteria. Therefore, the use of Table 3-5 may not be as accurate as individual retardance class charts when a design velocity is the determining factor.

Step 13: Check to see if temporary liner is needed for the vegetated channel, if so select lining to try and use *n* value from manufacturer or Table 3-7.

Q_2 = 11.8 cfs, Bottom width (b) = 3.0 ft, M= 3
n = 0.02 (Use basic *n* value for channels cut in earth (Table 3-4)
Vp = 2.0 ft/sec maximum allowable velocity for bare soil
Channel gradient = 2%

Using Manning's equation:

B (ft)	y (ft)	A (ft^2)	R (ft)	V (ft/s)	Q (cfs)	Comments
3	0.5	2.23	0.36	5.35	11.9	V>Vp protection/liner is required

Step 14: Calculate channel design using straw matting (double net) as temporary liner.
n = 0.028 (Table 3-7); Td = 1.75 (Table 3-8)

b (ft)	y (ft)	A (ft^2)	R (ft)	V (ft/s)	Q (cfs)
3	0.59	2.83	0.42	4.21	11.9

Step 15: Calculate shear stress for Q_2 conditions:

$$T = \omega ds \quad (3.3)$$

T = (62.4)(0.59)(0.02) = 0.74

Step 16: Compare calculated T with permissible shear T_d:
If T <T_d then OK**
T= 0.74 (Step 15)
T_d = 1.75 (Table 3-7)
0.74 < 1.75, OK**
Temporary liner: straw with net.

(**In some cases the solution is not as clearly defined; the use of a more conservative material is recommended.)

Channel Summary:

Channel is trapezoidal with a 3 foot bottom, 3:1 side slopes, 2 foot total depth, and 2% channel slope. Channel is lined with straw matting (double net).

Table 3-7
Manning's Roughness Coefficient for
Temporary Lining Materials

	***n* value for Depth Ranges**		
Lining Type	**0-0.5 ft**	**0.5-2.0 ft**	**>2.0 ft**
Straw matting (double net)	0.055	0.028	0.021
70% straw/30% coconut matting (double net)	0.050	0.025	0.018
Coconut matting (double net)	0.022	0.014	0.014
Coconut matting (triple, permanent net)	0.041	0.018	0.012

Application Note: The designer is responsible for providing documentation for design values of roughness (n). The n values listed in Table 3-6 may not conform to the values of any specific manufacturer.

Table 3-8
Permissible Shear Stresses for Riprap and Temporary Liners

Lining Category	Lining Type	Permissible Unit Shear Stress T_d (lb/ft^2)
Temporary	Straw matting (double net)	1.75
	70%Straw/30% Coconut matting (double net)	2.00
	Coconut matting (double net)	2.25
	Coconut matting (triple, permanent net)	3.00

Application Note: The designer is responsible for providing documentation of design values for allowable stress and velocity of proprietary linings. The permissible shear stress values listed in Table 3-8 may not conform to the values of any specific manufacturer.

Lining Category	d_{50} Stone Size (inches)	Permissible Unit Shear Stress T_d (lb/ft^2)
Gravel Riprap	1	0.33
	2	0.67
Rock Riprap	6	2.00
	9	3.00
	12	4.00
	15	5.00
	18	6.00
	21	7.80
	24	8.00

Application Note: The designer is responsible for specifying the proper depth and size for riprap used either as a channel lining or as an energy dissipator.

3.5 RIPRAP DESIGN

3.5.1 Assumptions

This procedure applies to riprap placement in both natural and prismatic channels and has the following assumptions and limitations:

1. Maximum side slope is 2:1
2. Maximum allowable velocity is 14 feet per second

If significant turbulence is caused by boundary irregularities, such as installations near obstructions or structures, this procedure is not applicable. Where riprap is used in ditches/channels that are 2% or less, the design should take into account the potential for sedimentation.

3.5.2 Procedure for Riprap Channel Design

Following are the steps in the procedure for riprap design.

1. Determine the average velocity in the main channel for the design condition. Use the higher value of velocity calculated both with and without riprap in place (this may require iteration using procedures in Appendix 3C.4). Manning's *n* values for riprap can be calculated from the equation:

$$\mathbf{n = 0.0395\ (d_{50})^{1/6}} \qquad \mathbf{(3.5)}$$

   Where: n = Manning's roughness coefficient for stone riprap

   d_{50} = diameter of stone for which 50 percent, by weight, of the gradation is finer (ft)

2. If rock is to be placed at the outside of a bend, multiply the velocity determined in Step 1 by the bend correction coefficient, C_b, given in Figure 3-4 for either a natural or prismatic channel. This requires determining the channel top width, W, just upstream from the bend and the centerline bend radius, R_b.

3. If the specific weight of the stone varies from 165 pounds per cubic foot, multiply the velocity from Step 1 or 2 (as appropriate) by the specific weight correction coefficient, C_g, from Figure 3-5.

4. Determine the required minimum d_{30} value from Figure 3-6 which is based on the equation:

$$\mathbf{d_{30}/D = 0.193\ Fr^{2.5}} \qquad \mathbf{(3.6)}$$

   Where: d_{30} = diameter of stone for which 30 percent, by weight, of the gradation is finer (ft)

   D = depth of flow above stone (ft)

   Fr = Froude number (see equation D.3), dimensionless

   v = mean velocity above the stone (ft/s)

   g = acceleration due to gravity (32.3 ft/sec^2)

5. Determine available riprap gradations. A well graded riprap is preferable to uniform size or gap graded. The diameter of the largest stone, d_{100}, should not be more than 1.5 times the d_{50} size. Blanket thickness should be greater than or equal to d_{100} except as noted below. Sufficient fines (below d_{15}) should be available to fill the voids in the larger rock sizes. The stone weight for a selected stone size can be calculated from the equation:

$$\mathbf{w = 0.5236\ SW_s\ d^3} \qquad \mathbf{(3.7)}$$

   Where: w = stone weight (lbs)

   d = selected stone diameter (ft)

   SW_s = specific weight of stone (lbs/ft^3)

Filter fabric or a filter stone layer should be used to prevent turbulence or groundwater seepage from removing bank material through the stone or to serve as a foundation for unconsolidated material. Layer thickness should be increased by 50 percent for underwater placement.

6. If d_{85}/d_{15} is between 2.0 and 2.3 and a smaller d_{30} size is desired, a thickness greater than d_{100} can be used to offset the smaller d_{30} size. Figure 3-7 can be used to make an approximate adjustment using the ratio of d_{30} sizes. Enter the y-axis with the ratio of the desired d_{30} size to the standard d_{30} size and find the thickness ratio increase on the x-axis. Other minor gradation deficiencies may be compensated for by increasing the stone blanket thickness.

7. Perform preliminary design, ensuring that adequate transition is provided to natural materials both up and downstream to avoid flanking and that toe protection is provided to avoid riprap undermining.

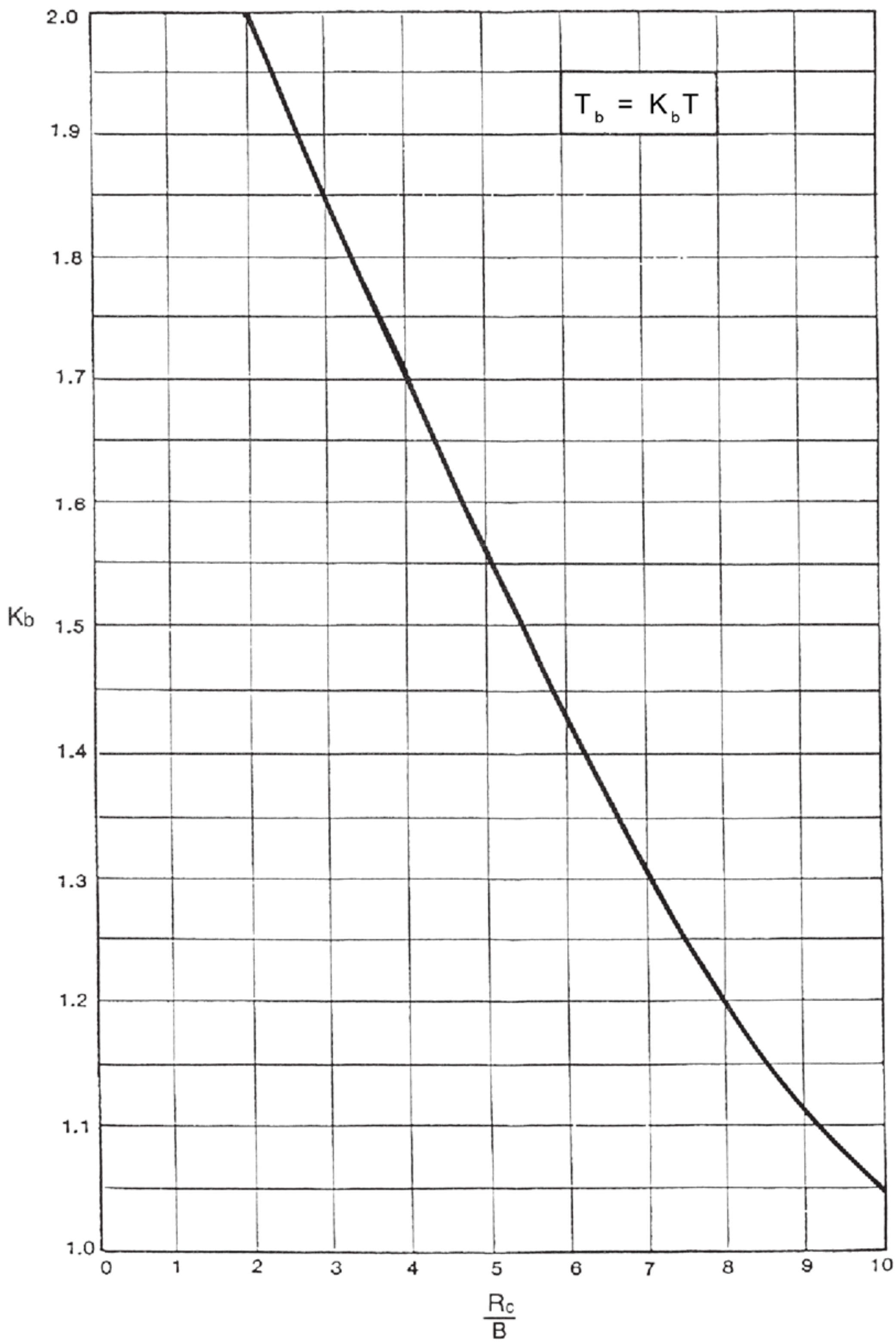


Figure 3-2 K_b Factor for Maximum Shear Stress on Channel Bends
Source: www.dlr.enr.state.nc.us/images/Sediment_design_manual_June2006/ChapterEight_20070419.PDF, page 607

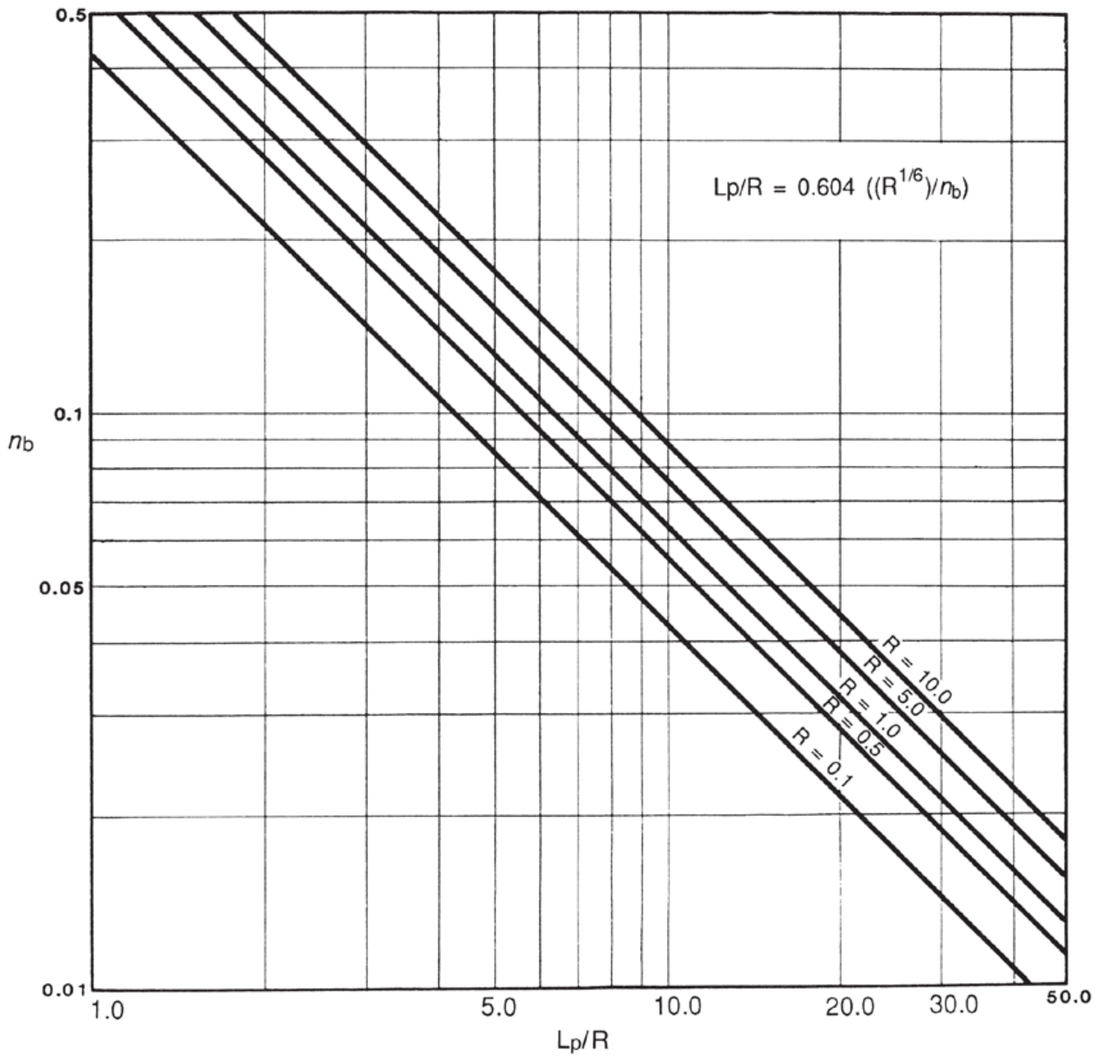


Figure 3-3 Protection Length, L_p, Downstream from Channel Bend.

n_b = Manning's Roughness of the lining material in the bend and the depth of flow
R = Hydraulic Radius = Area/wetted perimeter

Source: www.dlr.enr.state.nc.us/images/Sediment_design_manual_June2006/ChapterEight_20070419.PDF, page 608

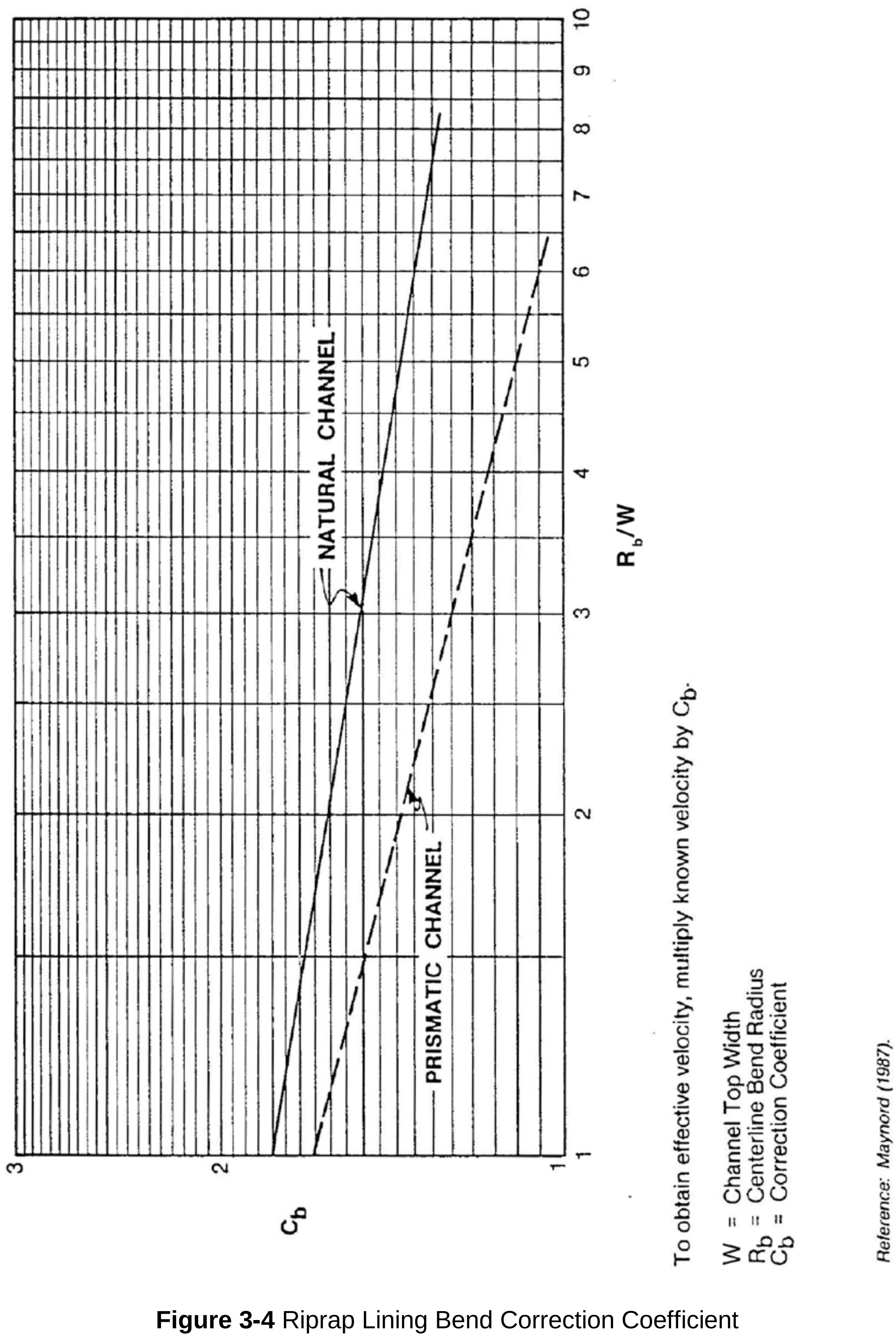


Figure 3-4 Riprap Lining Bend Correction Coefficient
Source: Georgia Stormwater Management Manual, Volume 2, 4.4-23

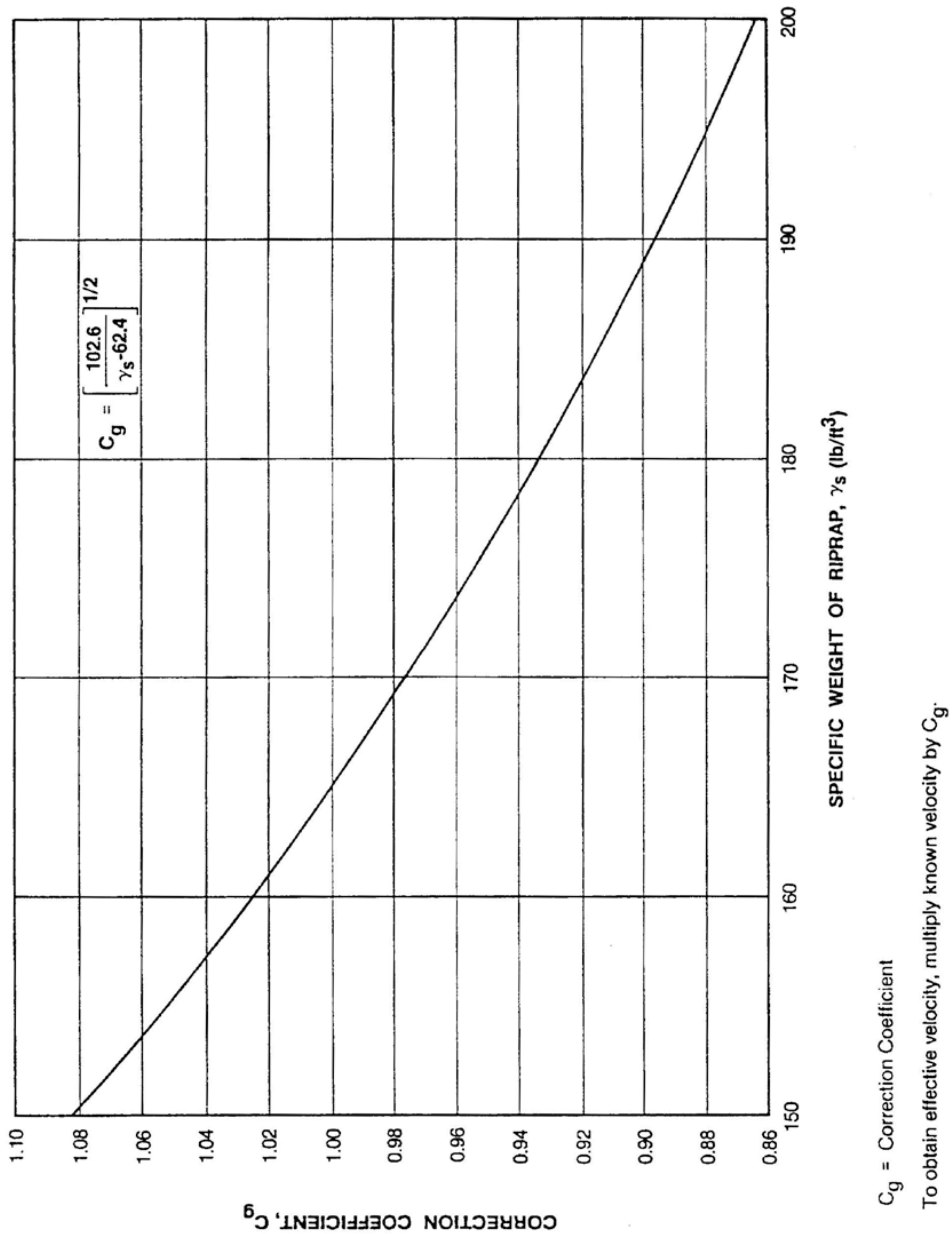


Figure 3-5 Riprap Lining Specific Weight Correction Coefficient
Source: Nashville Storm Water Management Manual, 1988

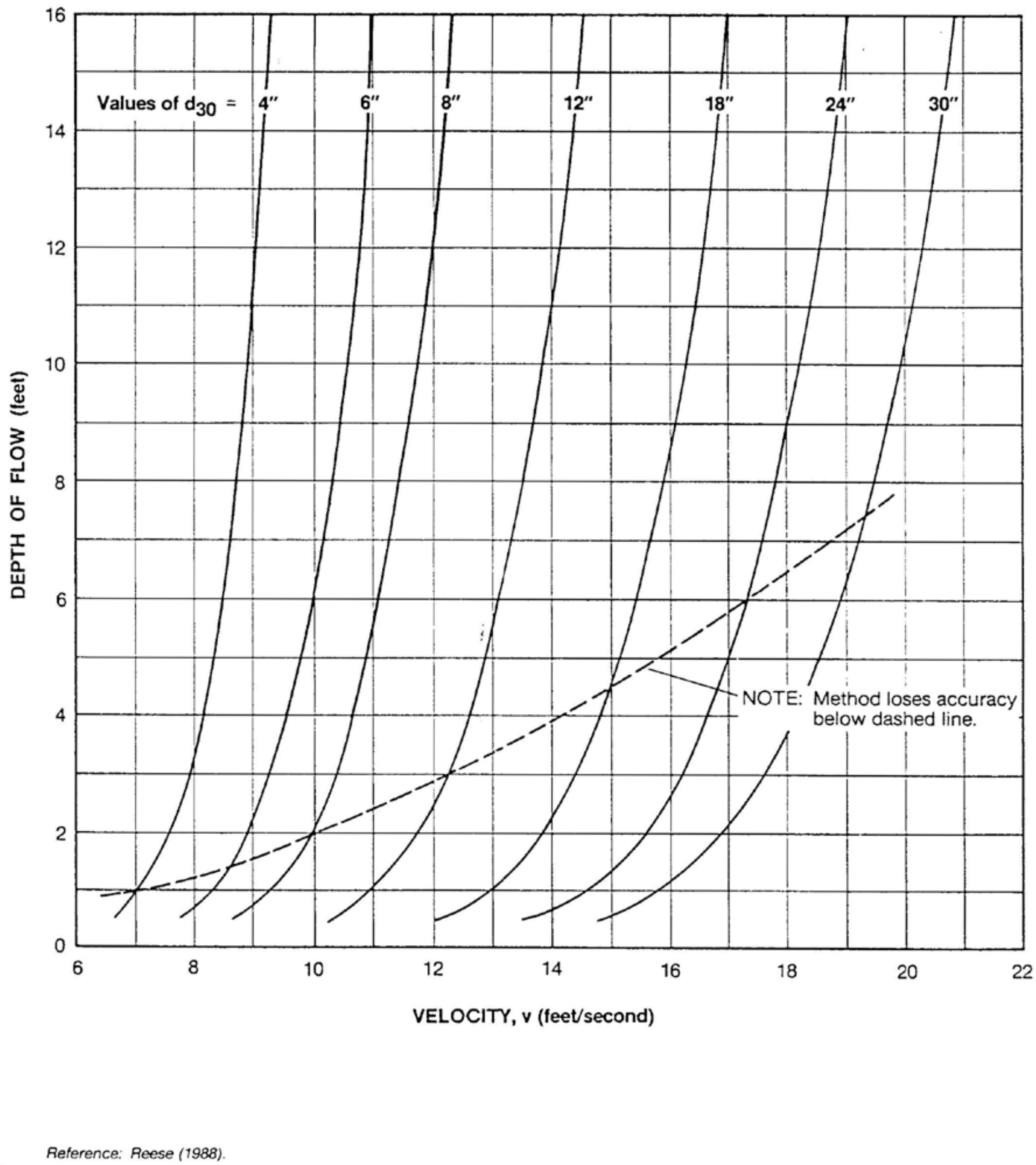


Figure 3-6 Riprap Lining d_{30} Stone Size - Function of Mean Velocity and Depth
Source: Georgia Stormwater Management Manual, Volume 2, 4.4-25

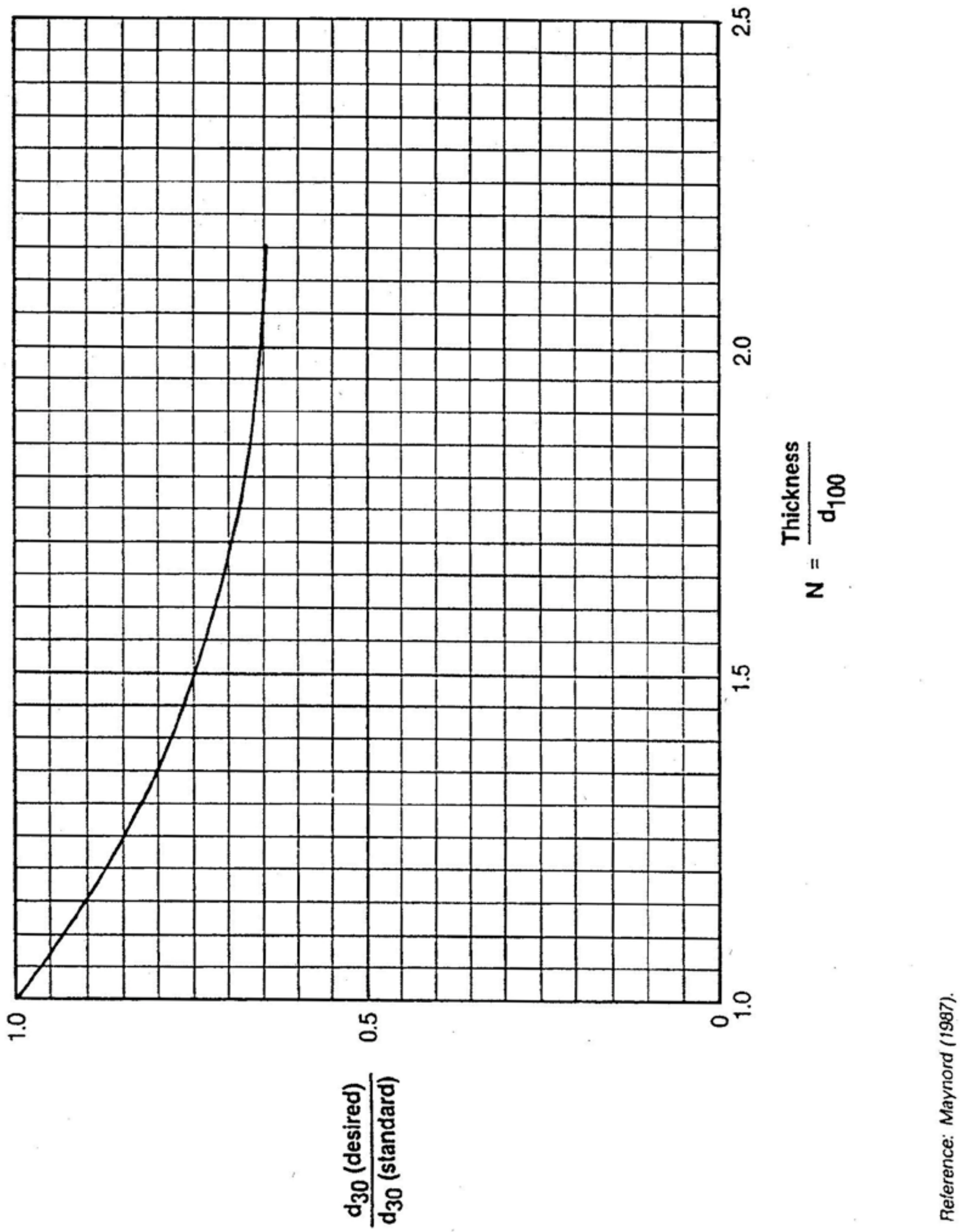


Figure 3-7 Riprap Lining Thickness Adjustment for d_{85}/d_{15} = 2.0 to 2.3
Source: Georgia Stormwater Management Manual, Volume 2, 4.4-27

3.6 APPROXIMATE FLOOD LIMITS

3.6.1 Introduction

For streams and tributaries with drainage areas smaller than one square mile, analysis may be required to identify the 100-year flood elevation and building restriction floodline. This requires a backwater analysis to determine the stream flow depth. The HEC-RAS software package is an acceptable method.

3.6.2 Floodline Restrictions

For such cases when the design engineer can demonstrate that a complete backwater analysis is unwarranted, approximate methods may be used.

A generally accepted method for approximating the 100-year flood elevation is outlined as follows:

1. Divide the stream or tributary into reaches that may be approximated using average slopes, cross sections, and roughness coefficients for each reach. The maximum allowable distance between cross sections is 100 feet.

2. Estimate the 100-year peak discharge for each reach using an appropriate hydrologic method from Hydrology Chapter 2.

3. Compute normal depth for uniform flow in each reach using Manning’s equation for the reach characteristics from Step 1 and peak discharge from Step 2.

4. Use the normal depths computed in Step 3 to approximate the 100-year flood elevation in each reach. The 100-year flood elevation is then used to delineate the flood plain.

This approximate method is based on several assumptions, including, but not limited to, the following:

1. A channel reach is accurately approximated by average characteristics throughout its length.

2. The cross-sectional geometry, including area, wetted perimeter, and hydraulic radius, of a reach may be approximated using typical geometric properties that can be used in Manning’s equation to solve for normal depth.

3. Uniform flow can be established and backwater effects are negligible between reaches.

4. Expansion and contraction effects are negligible.

As indicated, the approximate method is based on a number of restrictive assumptions that may limit the accuracy of the approximation and applicability of the method. The engineer is responsible for appropriate application of this method.

APPENDIX 3A
HYDRAULIC TERMS

3A.1 Energy of Flow

Flowing water contains energy in two forms—potential and kinetic. The potential energy at a particular point is represented by the depth of the water plus that elevation of the channel bottom above a convenient datum plane. The kinetic energy (in feet) is represented by the velocity head, $V^2/2g$. Figure 3A-1 illustrates open channel energy concepts and equation 3A.1 is the energy equation.

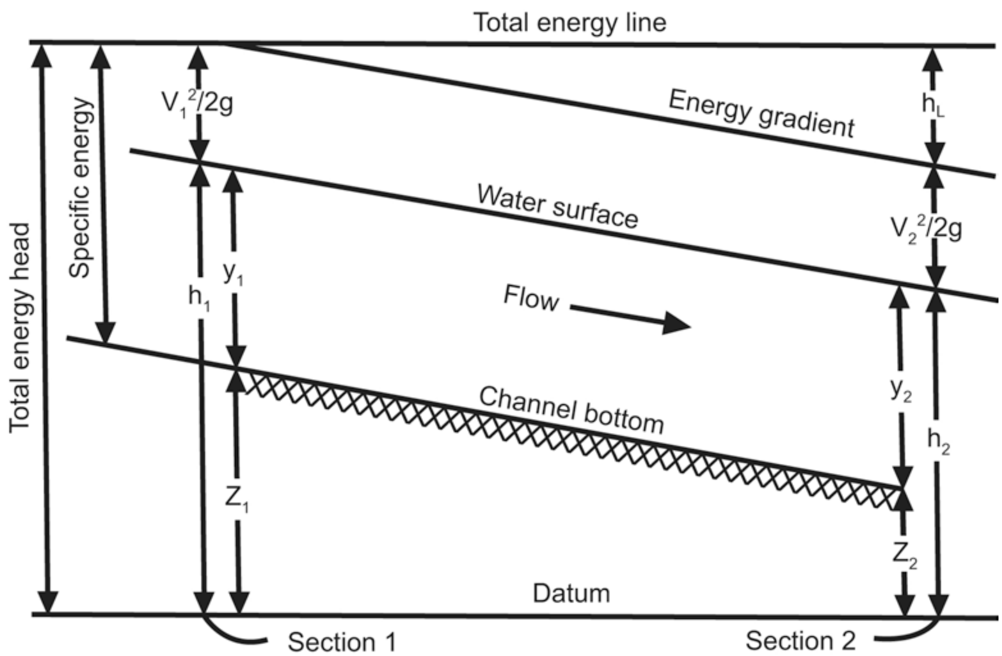


Figure 3A-1 Energy in Open Channel Flow

$$y_1 + V_1^2/2g + Z_1 = y_2 + V_2^2/2g + Z_2 + h_L \qquad \textbf{(3A.1)}$$

Where: y = depth of flow above streambed (ft)

V = mean velocity of flow (ft/s)

Z = vertical distance from datum (ft)

g = acceleration due to gravity (32.2 ft/s^2)

h_L = head loss (ft)

The slope (gradient) of the total energy grade line is a measure of the friction slope or rate of energy head loss due to friction. The total head loss for a length of channel is the product of the length and friction slope (h_L = S x L). Under uniform flow, the energy line is parallel to the water surface and streambed.

3A.2 Steady and Unsteady

Flow in open channels is classified either as steady or unsteady flow. Steady flow occurs when discharge or rate of flow at any cross section is constant with time. In unsteady flow, the discharge or rate of flow varies from one cross-section to another with time.

3A.3 Uniform and Non-Uniform Flow

Uniform flow exists when the channel cross-section, roughness, and slope are constant; and non-uniform or varied flow exists when the channel properties vary from section to section.

3A.4 Froude Number

The Froude Number is the ratio of the inertial force to that of gravitational force, expressed by the following equation:

$$\mathbf{Fr = v / (gD)^{1/2}} \qquad \textbf{(3A.2)}$$

Where: v = mean velocity of flow (ft/s)

g = acceleration due to gravity (32.2 ft/s^2)

D = hydraulic depth (ft) – defined as the cross sectional area of water normal to the direction of channel flow divided by free surface width.

3A.5 Critical Flow

Critical flow is defined as the condition for which the Froude Number is equal to one. At that state of flow, the specific energy is a minimum for a constant discharge. By plotting specific energy head against depth of flow for a constant discharge, a specific energy diagram can be drawn as illustrated in Figure 3A-2. Also, by plotting discharge against specific energy head we can illustrate not only minimum specific energy for a given discharge per unit width, but also maximum discharge per unit for a given specific energy.

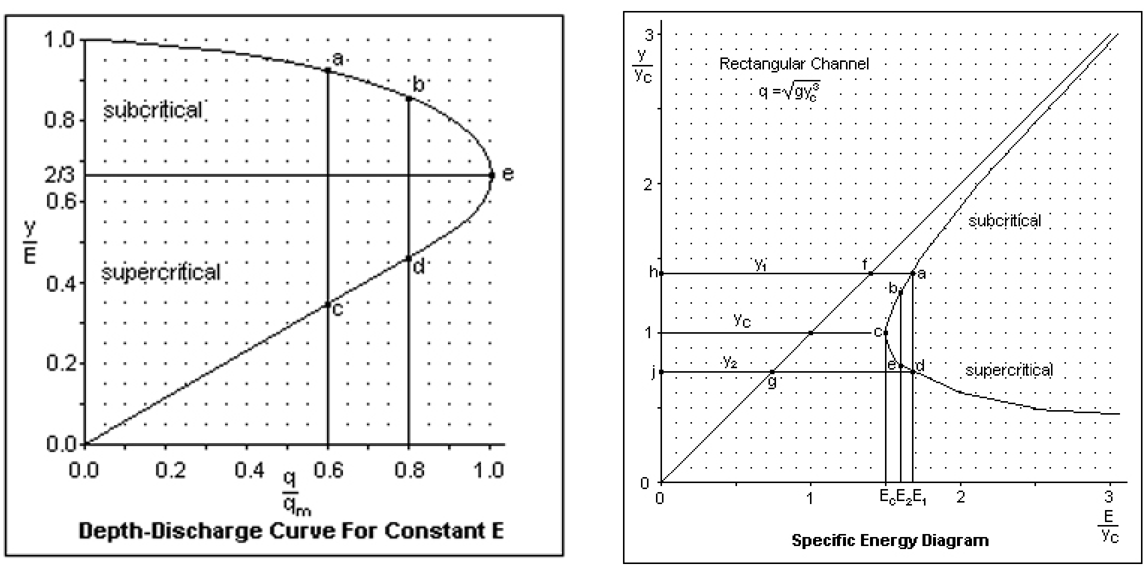


Figure 3A-2 Definition Sketch of Specific Energy

3A.6 Subcritical Flow

When the Froude Number is smaller than 1, the state of flow is defined as subcritical or tranquil flow, and surface waves propagate upstream as well as downstream. Control of subcritical flow depth is always downstream.

3A.7 Supercritical Flow

When the Froude Number is larger than 1, the state of flow is defined as supercritical or rapid flow, and surface disturbance can propagate only in the downstream direction. Control of supercritical flow depth is always at the upstream end of the critical flow region.

APPENDIX 3B
BEST HYDRAULIC SECTION

3B.1 Introduction

For a given discharge, slope and channel roughness, maximum velocity implies minimum cross sectional area. From Manning's equation, if velocity is maximized and area is minimized, wetted perimeter will also be minimized. The best hydraulic section therefore, simultaneously minimizes area and wetted perimeter.

For ease of construction, most channels are built with trapezoidal cross-sections. Therefore, this chapter deals with computing the best hydraulic section for trapezoidal section channels.

3B.2 Equations

Given that the desired side slope, M to one, has been selected for a given channel, the minimum wetted perimeter (P) exists when:

$$\mathbf{P = 4y\,(1 + M^2)^{1/2} - 2My} \qquad \textbf{(3B.1)}$$

Where: P = wetted perimeter (ft)

y = depth of flow (ft)

M= side slope, M to 1

(Figure D-1 below shows a definition of variables.)

From the geometry of the channel cross-section and the Manning's equation, design equations can be developed for determining the dimensions of the best hydraulic section for a trapezoidal channel.

The depth of the best hydraulic section is defined by:

$$\mathbf{y = C_M\,(Qn/(S^{1/2}))^{3/8}} \qquad \textbf{(3B.2)}$$

Where:

$$\mathbf{C_M = \left[\frac{\{k + 2(M^2 + 1)^{1/2}\}^{2/3}}{1.49\,(k + M)^{5/3}}\right]^{3/8}} \qquad \textbf{(3B.3)}$$

The associated bottom width is:

$$\mathbf{b = ky} \qquad \textbf{(3B.4)}$$

The cross-sectional area of the resulting channel is:

$$\mathbf{A = by + My^2} \qquad \textbf{(3B.5)}$$

where: y = depth of flow (ft)

C_M = coefficient

n = Manning's roughness coefficient

Q = discharge rate (cfs)

S = slope (ft/ft)

M = sideslope, M to 1

k = coefficient

A = cross-sectional area (ft^2)

Table 3B -1 lists values of C_M and k for various values of M.

Table 3B-1

Best Hydraulic Section Coefficients

Values of C_M and k for determining bottom width and depth of best hydraulic section for a trapezoidal channel.

M	C_M	k
0/1	0.790	2.00
0.5/1	0.833	1.236
0.577/1	0.833	1.155
1.0/1	0.817	0.828
1.5/1	0.775	0.606
2.0/1	0.729	0.472
2.5/1	0.688	0.385
3.0/1	0.653	0.325
3.5/1	0.622	0.280
4.0/1	0.595	0.246
5.0/1	0.522	0.198
6.0/1	0.518	0.166
8.0/1	0.467	0.125
10.0/1	0.430	0.100
12.0/1	0.402	0.083

APPENDIX 3C
OPEN CHANNEL FLOW CALCULATIONS

3C.1 Design Charts

Following is a discussion of the equations that can be used for the design and analysis of open channel flow. The Federal Highway Association has prepared numerous design charts to aid in the design of rectangular, triangular and trapezoidal open channel cross sections. In addition, design charts for grass-lined channels have been developed. For a complete discussion of these charts and their use in open channel design refer to the publication *Design Charts for Open Channel Flow*, Federal Highway Administration, Hydraulic Design Series No. 3, 1973.

3C.2 Manning's Evaluation

Manning's equation, presented in three forms below, is recommended for evaluating uniform flow conditions in open channels:

$$v = (1.49/n)R^{2/3}S^{1/2} \quad (3C.1)$$

$$Q = (1.49/n)A\,R^{2/3}\,S^{1/2} \quad (3C.2)$$

$$S = [Qn/(1.49\,A\,R^{2/3})]^2 \quad (3C.3)$$

Where: v = average channel velocity (ft/s)

Q = discharge rate for design conditions (cfs)

n = Manning's roughness coefficient

A = cross-sectional area (ft^2)

R = hydraulic radius (ft)

S = slope of the energy grade line (ft/ft)

For prismatic channels, in the absence of backwater conditions, the slope of the energy grade line and channel bottom are equal.

3C.3 Geometric Relationships

Area, wetted perimeter, hydraulic radius, and channel top width for standard channel cross-sections can be calculated from their geometric dimensions. Irregular channel cross sections (i.e., those with a narrow deep main channel and a wide shallow overbank channel) must be subdivided into segments so that the flow can be computed separately for the main channel and overbank portions. This same process of subdivision may be used when different parts of the channel cross section have different roughness coefficients. When computing the hydraulic radius of the subsections, the water depth common to the two adjacent subsections is not counted as wetted perimeter.

3C.4 Normal Depth Solutions

A trial and error procedure for solving Manning's equation is used to compute the normal depth of flow in a uniform channel when the channel shape, slope, roughness and design discharge are known. For purposes of the trial and error process, Manning's equation can be arranged as:

$$AR^{2/3} = (Qn)/(1.49\ S^{1/2}) \quad \textbf{(3C.4)}$$

Where: A = cross-sectional area (ft)

R = Hydraulic radius (ft)

Q = discharge rate for design conditions (cfs)

n = Manning's roughness coefficient

S = slope of the energy grade line (ft/ft)

To determine the normal depth of flow in a channel by the trial and error process, trial values of depth are used to determine A, P and R for the given channel cross section. Trial values of $AR^{2/3}$ are computed until the equality of equation 3C.4 is satisfied such that the design flow is conveyed for the slope and selected channel cross section.

Graphical procedures for simplifying trial and error solutions are presented in Figure 3C-1 for trapezoidal channels, which is described below.

1. Determine design discharge, Q, Manning's *n* value, channel bottom width (b), channel slope (S). and channel side slope (M).

2. Calculate the trapezoidal conveyance factor using the equation:

$$K_T = (Qn)/(b^{8/3}S^{1/2}) \quad \textbf{(3C.5)}$$

Where: K_T = Trapezoidal open channel conveyance factor

Q = Discharge rate for design conditions (cfs)

n = Manning's roughness coefficient

b = bottom width (ft)

S = slope of the energy grade line (ft/ft)

3. Enter the x-axis of Figure 3C-1 with the value of K_T calculated in Step 2 and draw a line vertically to the curve corresponding to the appropriate M value from Step 1.

4. From the point of intersections obtained in Step 3, draw a horizontal line to the y-axis and read the value of the normal depth of flow over the bottom width, y/b.

5. Multiply the y/b value from Step 4 by b to obtain the normal depth of flow.

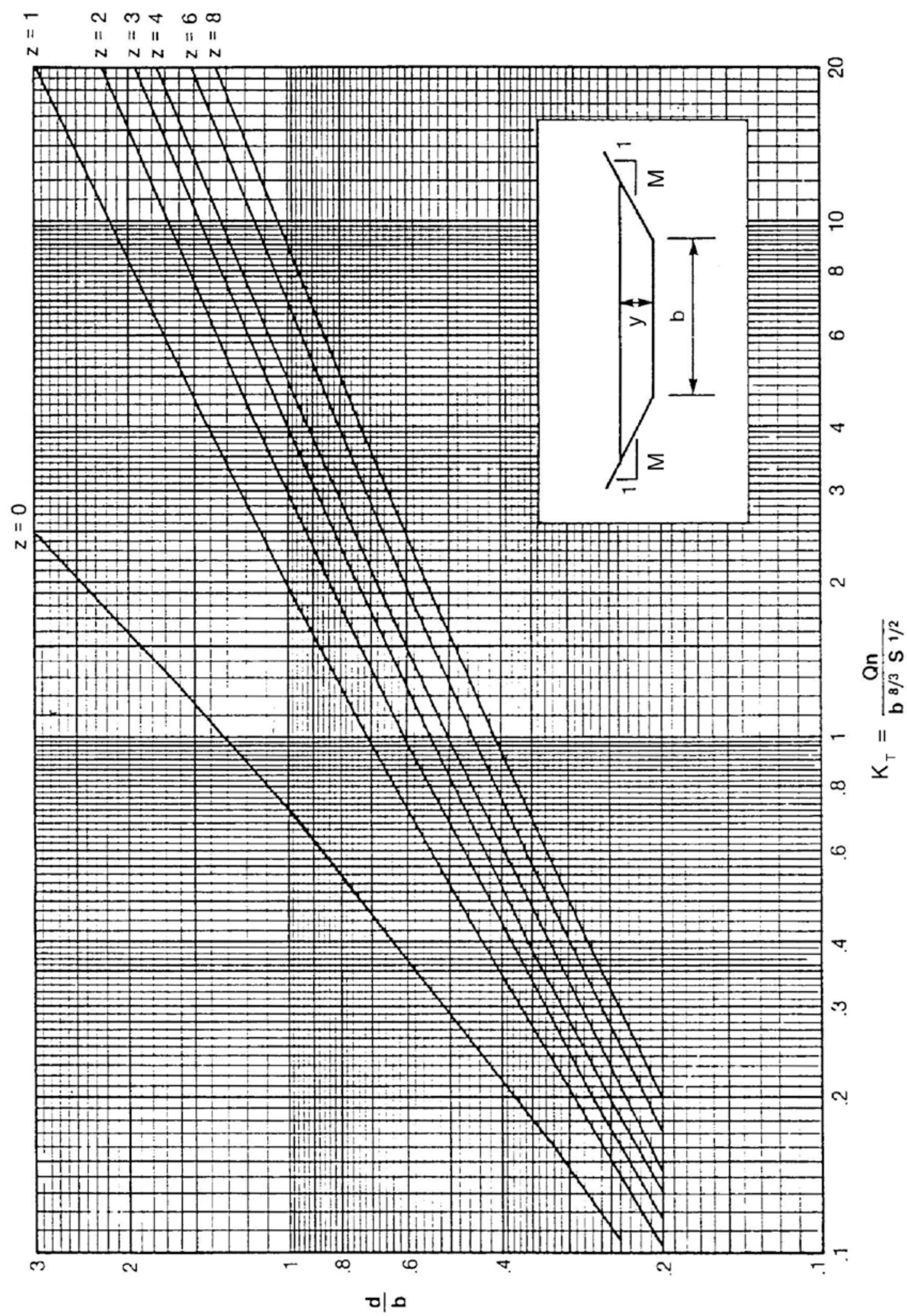


Figure 3C-1 Trapezoidal Channel Capacity Chart
Source: Georgia Stormwater Management Manual, Volume 2, 4.4-15

APPENDIX 3D
CRITICAL FLOW CALCULATIONS

3D.1 Background

Critical depth depends only on the discharge rate and channel geometry. The general equation for determining critical depth is expressed as:

$$Q^2/g = A^3/W \qquad \textbf{(3D.1)}$$

Where: Q = discharge rate for conditions (cfs)

g = acceleration due to gravity (32.2 ft/sec^2)

A = cross-sectional area (ft^2)

W = top width of water surface (ft)

A trial and error procedure is needed to solve equation D.1.

3D.2 Semi-Empirical Equations

Semi-empirical equations (as presented in Table 3D-1) or section factors (as presented in Figure 3D-1) can be used to simplify trial and error critical depth calculations. The following equation from Chow (1959) is used to determine critical depth with the critical flow section factor, Z:

$$Z = Q/(g^{1/2}) \qquad \textbf{(3D.2)}$$

Where: Z = critical flow section factor

Q = discharge rate for design conditions (cfs)

g = acceleration due to gravity (32.2 ft/sec^2)

The following guidelines are presented for evaluating critical flow conditions of open channel flow:

1. A normal depth of uniform flow within 10 percent of critical depth is unstable and should be avoided in design, if possible.

2. If the velocity head is less than one-half the mean depth of flow, the flow is subcritical.

3. If the velocity head is equal to one-half the mean depth of flow, the flow is critical.

4. If the velocity head is greater than one-half the mean depth of flow, the flow is supercritical.

5. If an unstable critical depth cannot be avoided in design, the least type of flow should be assumed for the design.

3D.3 Froude Number

The Froude Number, Fr, calculated by the following equation, is useful for evaluating the type of flow conditions in an open channel:

$$\mathbf{Fr = v / (gA/W)^{1/2}} \qquad \textbf{(3D.3)}$$

Where: Fr = Froude number (dimensionless)

v = velocity of flow (ft/s)

g = acceleration due to gravity (32.2 ft/sec^2)

A = cross-sectional area of flow (ft^2)

W = top width of flow (ft)

If Fr is greater than 1.0, flow is supercritical; if is under 1.0 flow is subcritical. Fr equals 1.0 for critical flow conditions.

Table 3D-1
Critical Depth Equations for Uniform Flow in Channel Cross Sections

Channel Type[a]	Semi-Empirical Equation[b] for Estimating Critical Depth	Range of Applicability
1. Rectangular[c]	$y_c = (Q^2/gb^2)^{1/3}$	N/A
2. Trapezoidal	$y_c = 0.81(Q^2/gM^{0.75}b^{1.25})^{0.27}-(b/30M)$	$0.1<0.5522(Q/b^{2.5})<0.4$, For $0.5522\ (Q/b^{2.5})< 0.1$, use rectangular channel equation
3. Triangular[c]	$y_c = [(2Q^{2)}/(gM^2)]^{1/5}$	N/A
4. Circular[d]	$y_c = 0.325(Q/D)^{2/3} + 0.083D$	$0.3 < y_c/D < 0.9$
5. General[e]	$A^3/W = (Q^2/g)$	N/A

Where: y_c = Critical depth, in feet
Q = Design discharge, in cfs
g = Acceleration due to gravity, 32.2 feet/second^2
b = Bottom width of channel, in feet
M = Side slopes of a channel (horizontal to vertical)
D = Diameter of circular conduit, in feet
A = Cross-sectional area of flow, in square feet
W = Top width of water surface, in feet

[a] See Figure D-1 for channel sketches
[b] Assumes uniform flow with the kinetic energy coefficient equal to 1.0
[c] Reference: French (1985)
[d] Reference: USDOT, FHWA, HDS-4 (1965)
[e] Reference: Brater and King (1976)

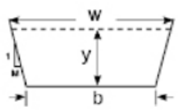
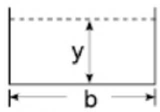
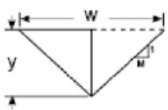
Section	Area A	Wetted Perimeter, P	Hydraulic Radius, R	Top Width, W	Critical Depth Factor, Z
 Trapezoid	$by + My^2$	$b + 2y(M^2+1)^{1/2}$	$\frac{by + My^2}{b + 2y\sqrt{M^2 + 1}}$	$b + 2My$	$\frac{[(b + My)y]^{1.5}}{\sqrt{b + 2My}}$
 Rectangle	by	$b + 2y$	$\frac{by}{b + 2y}$	b	$by^{1.5}$
 Triangle	My^2	$2y\sqrt{M^2 + 1}$	$\frac{My}{2\sqrt{M^2 + 1}}$	$2My$	$\frac{\sqrt{2}}{2} My^{2.5}$

Figure 3D-1 Open Channel Geometric Relationships for Various Cross Sections