CHAPTER 6. OPEN CHANNEL FLOW DESIGN

CONTENTS

Section Page OC-

TABLES

FIGURES

1.0 INTRODUCTION

1.1 Purpose of the Chapter

The purpose of this chapter is to provide guidance for designing facilities to convey stormwater runoff in open channels. The goal of open channels is to convey stormwater runoff from, and through urban drainage areas without damage to adjacent properties/developments; to the open channel; or to the storm drainage system connected to it. Specifically this chapter provides information on physical channel criteria and design methodology necessary to design open channels according to City requirements.

This chapter addresses the major topics related to the design of open channels, beginning with essential background on the issues of open channel planning and engineering (Section 1.4) and fluvial geomorphology(Section 1.5). General open channel hydraulics and preliminary design criteria are presented in Section 2.0. It is the responsibility of the designer to be knowledgeable of open channel hydraulics, and, therefore, the key principles and equations are reviewed without extensive background of the subject matter, theoretical considerations, etc. Section 3.0 contains specific design criteria for a variety of channel types and includes example calculations, typical cross sections, and other representative design details.

1.2 General

Major drainage is the cornerstone of an urban storm runoff system. The major drainage system will exist whether or not it has been planned and designed, and whether or not urban development is wisely located in respect to it. Thus, major drainage must be given high priority when considering drainage improvements.

A core component of any major drainage system is open channels. Open channels are the most common major drainage system component used to transport all of the stormwater runoff collected in drainage systems. Open channels are versatile and come in several different types and consist of several different channel components. Open channels are in effect the final instrument within a drainage system for handling stormwater and as such have the final interaction with stormwater before it flows into a major river or other large body of water.

While the primary function of open channels is conveyance of runoff, many design decisions contribute to the role of channels in the urban environment in terms of stability, multiple use benefits, social acceptance, aesthetics, resource management, and maintenance. It is important for the engineer to be involved from the very start of a land development project because this *Manual* has bearing on the critical planning decisions involved in route selection for open channels within the major drainage system. The importance of route selection cannot be overstated since the route selected will influence every element of the major drainage project from the cost to the type of channel used to the benefits derived by the community.

1.3 Types of Major Open Channels

The types of major drainage channels available to the designer are numerous. Section 2.3.1 describes in detail the types of channels engineers can consider as potential major open channels in urban areas and then select the one that best addresses the hydraulic requirements; environmental considerations; community impact; sociological needs; and permitting limitations. Table OC–6 lists the types of channels discussed within this chapter along with the City's attitude toward each channel type.

Table OC-1: Acceptable/Preferred Open Channel Types

Channel Type	**Preference Rating** [1] 1 – most preferred 4 – least preferred	**City approval required prior to implementation** [2]
Natural	1	No
Grass-lined	2	No
Composite	2	No
Concrete-lined	3	Yes
Riprap-lined	4	Yes
Bioengineered	2	No [3]

Notes:

1: Even though the City prefers to see specific channel types over others, the final channel type selected must be based on preference as well as applicability to the hydraulic conditions at hand.

2: Channel types listed as requiring City approval means the design engineer will have to address in the drainage report why the certain type of channel had to be used (i.e. R.O.W. constraints, hydraulic requirements, etc.) in lieu of the City's most preferred channel types. Additionally, written authorization from the City will be required prior to implementing a "lesser preferred" channel type into a final design.

3: Design of channel must be carried out and certified by a registered professional engineer.

As discussed in the rest of this chapter, the selection of the channel type for any given reach of a major drainageway is a complex function of hydraulic, hydrologic, structural, financial, environmental, sociological, public safety, and maintenance considerations and constraints. Table OC-1 merely provides preferences the design engineer should keep in mind when selecting an open channel type for a project.

Besides defining channel types by their lining characteristics, channels are further defined according to the maintenance classifications outlined in Section 2.5. Every open channel within the City of Bella Vista shall receive a designation as either primary, secondary, or tertiary which will establish the party responsible for maintaining a specific open channel in the City. Section 2.5 further defines the physical parameters of each type of these channels.

1.4 Issues in Open Channel Planning and Engineering

The most fundamental function of open channels is conveyance of the major storm runoff event, and an important characteristic is their stability during minor and major storms. Stability must be examined in the context of the future urbanized condition, in terms of both runoff events and altered base flow hydrology. *Base flow* within a channel is flow that is not caused by rainfall events, but rather aquifer seepage resulting from a variety of causes. Some of the most common base flow sources are springs, artesian groundwater, and other constant flow sources. Urbanization commonly causes base flows to increase, and the planner and engineer must anticipate and design for this increase.

In addition to stability issues, there are many planning and engineering decisions that contribute to the role of open channels in the urban environment, in terms of multiple use benefits, social acceptance, aesthetics, and resource management. The choices of the type and layout of open channels are of prime importance.

Open channels for transporting major storm runoff are the most desirable type of major drainageway because they offer many opportunities for creation of multiple use benefits such as incorporation of parks and greenbelts along the channel and other aesthetic and recreational uses that closed-conveyance drainageway designs preclude. Open channels are also usually less costly and they provide a higher degree of flood routing storage.

The choice of the type of open channel is a critical decision in planning and design of major drainageways. The preferred channel is a stable, natural one carved by nature over a long period of time that will remain stable after urbanization. Generally, the better an artificial channel's character matches a natural channel, it will be more functional and attractive. In an urban area, however, it is rarely feasible to leave a natural channel untouched since urbanization alters the hydrology of the watershed. Consequently, some level of stabilization is usually necessary to prevent the channel from degrading and eroding. Downstream channel evaluation should be done as part of the drainage report to determine the effects of development and in ascending order as shown in Table OC-1.

1.5 Fluvial Geomorphology

A drainage system within a watershed involves movement of water, thus the term *fluvial*. When flowing water develops a drainage pattern or surface forms, the process is identified as *fluvial geomorphology*. Surface form characteristics represented by open channels (natural and manmade) behave in complex manners that are dependent on watershed factors such as geology; soils; ground cover; land use; topography; and hydrologic conditions. These same watershed factors contribute to the sediment eroded from the watershed and transported by the stream channel. The sediments moved by the flowing water also influence channel hydraulic characteristics. The natural-like channel and stabilization systems recommended in this *Manual* are based on fluvial geomorphology principles. The remainder of this section will provide the reader with a basic understanding of the workings and evolution of open channels within an urban watershed.

1.5.1 Effects of Urbanization on Existing Stream Channels

In response to urbanization, existing open channels can undergo substantial changes if channel stabilization measures are not instituted in the early stages of urbanization. Urbanization causes (1) significant increases in peak discharges, total runoff volume, and frequency of bank-full discharges; (2) the steepening of channel slopes if and where natural channels are straightened to accommodate new development (a practice discouraged by the City); (3) reduction in sediment bedload from fully developed areas; and (4) eroding and degrading natural channels. These factors, in combination, create conditions that are conducive to channel instability—widening (erosion) and deepening (degradation) in most reaches and debris and sediment accumulation (aggradation) in others.

1.5.2 Stable Channel Balance

A stable channel is usually considered an alluvial channel in equilibrium with no significant change in channel cross section with time. This is a *dynamic equilibrium* in which the stream has adjusted its width, depth, and slope so that the channel neither aggrades nor degrades. Also, the sediment supply from upstream is equal to the sediment transport capacity of the channel. Under watershed conditions with normal hydrologic variations affecting runoff and sediment inflow, some adjustments in channel characteristics are inevitable.

Stable channel balance is well displayed in the relationship proposed by Lane (1955a) for the dynamic equilibrium concept whereby:

$$Q_W * S \propto Q_S * D_{50} \qquad \textbf{(Equation OC-1)}$$

in which:

Q_w = water discharge (cfs)

S = channel slope (ft/ft)

Q_s = bed material load (tons/day)

D_{50} = size of bed material (in)

For a stable channel, these four parameters are balanced, and, when one or more of the parameters changes, the others adjust to restore the state of equilibrium. For example, if the stream flow increased with no change in channel slope, there would be an adjustment on the sediment side of the balance, with an increase in bed material size, sediment load, or both. It is this principle for which the remaining open channel design equations and criteria are based in this chapter.

2.0 OPEN CHANNEL DESIGN PRINCIPLES

This section is intended to provide the designer with information necessary to perform open channel hydraulic analysis related to channel geometry, channel lining, and flow characteristics. This section includes preliminary design criteria and identifies considerations in selection of channel type.

2.1 General Open Channel Flow Hydraulics

When performing open channel design, hydraulic analysis must be completed to evaluate flow characteristics including flow regime, water surface elevations, velocities, depths, and hydraulic transitions for multiple flow conditions. Hydraulic grade lines and energy grade lines shall be prepared on all design projects.

The purpose of this section is to provide the designer with an overview of open channel flow hydraulics principles and equations relevant to the design of open channels. The reader should already be familiar with the open channel flow principles discussed in this section. Water surface profile computations are not addressed herein, and the reader is referred to other references [such as Chow (1959), Daugherty and Franzini (1977), and King and Brater (1963)] for discussion of that topic.

2.1.1 Types of Flow in Open Channels

Open channel flow can be characterized in many ways. Types of flow are commonly characterized by variability with respect to time and space. The following terms are used to identify types of open channel flow:

- *Steady flow*—rate of flow remains constant with time.
- *Unsteady flow*—rate of flow varies with time.
- *Uniform flow*—velocity and depth of flow remain constant over the length of the channel. If a channel is uniform and resistance and gravity forces are in exact balance, the water surface will be parallel to the bottom of the channel for uniform flow.
- *Varied flow*—velocity, discharge, depth, or other characteristics of the flow vary over the length of the channel stream. For a steady flow condition, flow is termed *rapidly varied* if these characteristics change over a short distance. If characteristics change over a longer stretch of the channel for steady flow conditions, flow is termed *gradually varied*.

For the purposes of open channel design, flow is usually considered steady and uniform. For a channel with a given roughness, discharge, and slope, there is only one possible depth for maintaining a uniform flow. This depth is the *normal depth*. When roughness, depth, and slope are known at a channel section, there can only be one discharge for maintaining a uniform flow through the section. This discharge is the *normal discharge*.

The designer should realize that uniform flow is more often a theoretical abstraction than an actuality (Calhoun, Compton, and Strohm 1971), namely, true uniform flow is difficult to find. Channels are sometimes designed on the assumption that they will carry uniform flow at the normal depth, but because of conditions that are difficult, if not impossible, to evaluate. This leads to not being taken into account, which results in flows that actually have depths considerably different from uniform depth. Uniform flow computation provides only an approximation of what will occur.

Manning's Equation describes the relationship between channel geometry, slope, roughness, and discharge for uniform flow:

$$Q = \frac{1.49}{n} * A * R^{2/3} * S^{1/2}$$ **(Equation OC-2)**

in which:

Q = discharge (cfs)

n = roughness coefficient

A = area of channel cross section (ft^2)

R = hydraulic radius = Area / Wetted Perimeter (P) (ft)

P = wetted perimeter (ft)

S = channel bottom slope (ft/ft)

Manning's Equation can also be expressed in terms of velocity by employing the continuity equation, $Q = VA$, as a substitution in Equation OC-2, where V is velocity (ft/sec).

For wide channels of uniform depth, where the width, b, is more than 25 times the depth, the hydraulic radius can be assumed to be equal to the depth, y, expressed in feet, and, therefore:

$$Q = \frac{1.49}{n} * b * y^{5/3} * S^{1/2}$$ **(Equation OC-3)**

$$y = \frac{Q^{0.6} * n^{0.6}}{1.27 * b^{0.6} * S^{0.3}}$$ **(Equation OC-4)**

$$S = \frac{(Q * n)^2}{2.2 * b^2 * y^{3.33}}$$ **(Equation OC-5)**

The solution of Equation OC-2 for depth is iterative.

2.1.2 Roughness Coefficients

When applying Manning's Equation, the choice of the roughness coefficient, *n*, is the most subjective parameter. Manning's *n* is affected by many factors and its selection, especially in natural channels which depend heavily on engineering experience. Table OC-2 provides guidance on values of roughness coefficients *n* to use for channel design. Both maximum and minimum roughness coefficients shall be used for channel design to check for sufficient hydraulic capacity and channel lining stability, respectively.

When using the retardance curves for grass-lined channels and swales (Figure OC-4), use Retardance C for finding Manning's *n* for determining channel capacity (depth) in a mature channel and Retardance D for checking the stability (velocity) in a newly constructed channel.

The designer should be aware that roughness greater than that assumed will cause the same discharge to flow at a greater depth, or conversely that flow at the computed depth will result in less discharge. Obstructions in the channel will cause an increase in depth above normal depth and must be taken into account. Sediment and debris in channels increase roughness coefficients, as well, and should be accounted for.

Table OC-2: Manning's *n* Roughness Coefficients for Channel Design (After Chow 1959)

Channel Type	Roughness Coefficient (*n*)		
	Min.	**Typical**	**Max.**
I. Excavated or Dredged			
1. Earth, straight and uniform			
a. Gravel, uniform section, clean	0.022	0.025	0.030
b. With short grass, few weeds	0.022	0.027	0.033
2. Earth, winding and sluggish			
a. Grass, some weeds	0.025	0.030	0.033
b. Dense weeds or aquatic plants	0.030	0.035	0.040
c. Earthy bottom and rubble/riprap sides	0.028	0.030	0.035
3. Channels not maintained, weeds and brush uncut			
a. Dense weeds, high as flow depth	0.050	0.080	0.120
b. Clean bottom, brush on sides	0.040	0.050	0.080
II. Natural streams (top width at flood stage ≥ 100 ft)			
1. Streams on plain			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. Clean, winding, some pools and shoals, some weeds and stones	0.035	0.045	0.050
c. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
III. Lined or Built-Up Channels			
1. Gravel bottom with sides of:			
a. Formed concrete	0.017	0.020	0.025
b. Random stone in mortar	0.020	0.023	0.026
c. Dry rubble or riprap	0.023	0.033	0.036
2. Concrete Lined Channels and Swales	See Table OC-10		
3. Composite (Wetland Bottom) Channels and Swales	See Section 3.2.1; Equation OC-11; Table OC-8		
4. Grass-Lined Channels and Swales	0.040 (capacity check); 0.030 (velocity check); or see Section 3.1.3, Figure OC-4		

2.1.3 Specific Energy of Channel Flow

Specific energy (E) of flow in a channel section is defined as the energy head relative to the channel bottom. If the channel slope is less than 10-percent and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy (E expressed as head in feet) becomes the sum of the depth and velocity head:

$$E = y + \frac{V^2}{2 * g} = y + \frac{Q}{2 * g * A^2} \qquad \textbf{(Equation OC-6)}$$

where:

y = Depth of flow (ft)

V = Mean flow velocity (ft/sec)

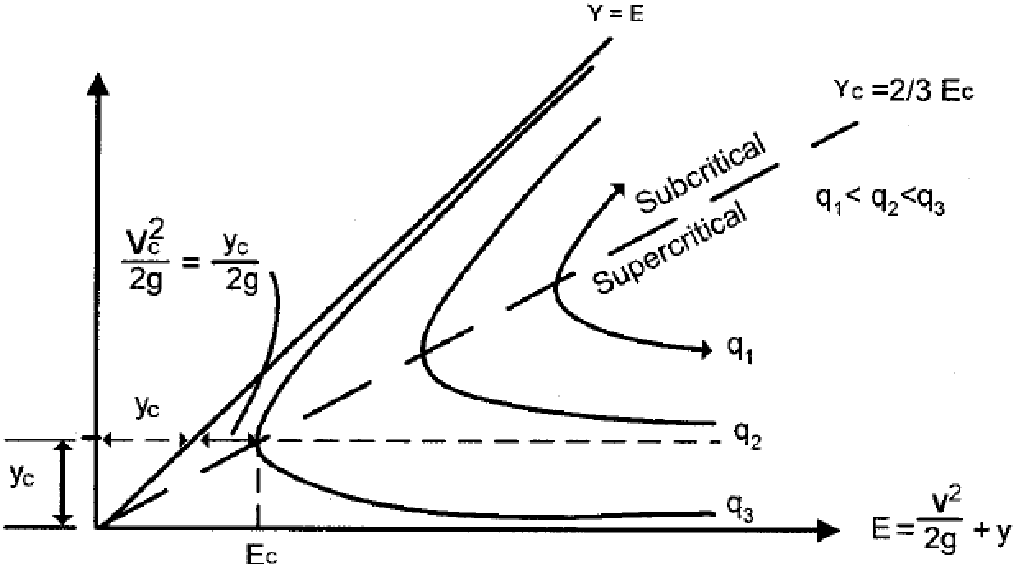
g = Gravitational acceleration (32.2 ft/sec^2)

Q = Discharge (ft^3/sec)

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

When specific energy is plotted against depth of flow, a curve with a minimum specific energy (E$_c$) results, as shown in Figure OC-1. At the minimum specific energy, E$_c$, the depth is called critical depth, y$_c$. Depths above critical depth, y$_c$, are subcritical, and below critical depth are supercritical (see additional discussion in Section 2.1.4).

Figure OC-1: Specific Energy Diagram for Rectangular Channels
(Bedient and Huber 2002)



$q_{\#}$ = Q for particular discharge curve

2.1.4 Flow Regime

Another important characteristic of open channel flow is the state of the flow, often referred to as the flow regime. Flow regime is determined by the balance of the effects of viscosity and gravity relative to the inertia of the flow. The Froude number, F_r, is a dimensionless number that is the ratio of inertial forces to gravitational forces that defines the flow regime. The Froude number is given by:

$$F_r = \frac{V}{\sqrt{g * d}}$$ **(Equation OC-7)**

in which:

V = Mean flow velocity (ft/sec)

g = Gravitational acceleration (32.2 ft/sec^2)

d = Hydraulic depth (ft) = A/T, cross-sectional area of water/width of free surface

Equation OC-7 applies to channel flow at any cross section. When:

- $F_r = 1.0$, flow is in a *critical* state
- $F_r < 1.0$, flow is in a *subcritical* state
- $F_r > 1.0$, flow is in a *supercritical* state

The following sections describe these flow regimes and associated criteria for channel design.

For all subcritical channels, check the Froude number using the *minimum* value of n for the relevant channel type from TableOC7. When performing hydraulic computations for grassed channels, the n values for the 0.1-foot to 1.5-feet flow depth range (Table OC-8) are generally suitable for calculating the wetted channel portion for the initial storm runoff. For major runoff computations, however, the greater than 3.0-feet depth n values (Table OC-8) are more appropriate since flows will tend to lay the grass down to form a smoother bottom surface.

2.1.4.1 Critical Flow

Critical flow in an open channel with a free water surface is characterized by several conditions (Fletcher and Grace 1972):

1. The specific energy is a minimum for a given flow rate (see Figure OC-1).
2. The discharge is a maximum for a given specific energy.
3. The specific force is a minimum for a given discharge.
4. The velocity head is equal to half the hydraulic depth in a channel of small slope.
5. The Froude number is equal to 1.0 (see Equation OC-7).
6. The velocity of flow in a channel of small slope is equal to the speed of small gravity waves in shallow water.

If the critical state of flow exists throughout an entire reach, the channel flow is critical flow, and the channel slope is at critical slope, S_{cr}. A slope less than S_{cr} will cause subcritical flow, and a slope greater than S_{cr} will cause supercritical flow. Critical depth is the depth of maximum discharge when the specific energy is held constant. A flow at or near the critical state is not stable and as such flows at Froude numbers between 0.8 and 1.2 shall be avoided. In design, if the depth is found to be at or near critical, the shape or slope should be changed to achieve greater hydraulic stability.

The general expression for flow at critical depth is:

$$\frac{Q^2}{g} = \frac{A^3}{T}$$

(Equation OC-8)

where:

Q = Discharge (cfs)

g = Gravitation acceleration (32.2 ft/sec^2)

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

T = Channel top width at the water surface (ft)

When flow is at critical depth, Equation OC-8 must be satisfied, regardless of the shape of the channel.

2.1.4.2 Subcritical Flow

Flows with a Froude number less than 1.0 are *subcritical* flows and have the following characteristics relative to critical flows (Maricopa County 2000):

1. Flow velocity is lower.
2. Flow depth is greater.
3. Hydraulic losses are lower.
4. Erosive power is less.
5. Behavior is easily described by relatively simple mathematical equations.
6. Surface waves can propagate upstream and downstream, and the control is always located downstream.

Most stable natural channels have *subcritical* flow regimes. Consistent with the City's philosophy that the most successful artificial channels utilize characteristics of stable natural channels, the drainage design should seek to create channels with *subcritical* flow regimes.

A concrete-lined channel shall not be used for subcritical flows except in unusual circumstances where a narrow right-of-way exists. A stabilized natural channel; a wide grass-lined channel; or a wetland-bottom channel is the most preferred. Design of a subcritical channel for a Froude number greater than 0.8 using the velocity and depth calculated with the lowest recommended range for Manning's n (Table OC-2) will not be permitted by the City. When designing a concrete-lined channel for subcritical flow, use a Manning's n = 0.013 for capacity calculations and 0.011 to check whether the flow could go supercritical. If significant sediment deposition or sediment transport is likely, a Manning's n greater than 0.013 may be necessary for capacity calculations.

2.1.4.3 Supercritical Flow

Flows with a Froude number greater than 1.0 are supercritical flows and have the following characteristics relative to critical flows (Maricopa County 2000):

1. Flows have higher velocities.
2. Depth of flow is shallower.
3. Hydraulic losses are higher.
4. Erosive power is greater.
5. Surface waves propagate downstream only.

Supercritical flow in an open channel in an urban area creates hazards that the designer must consider. From a practical standpoint, it is generally not practical to have curvature in a channel with supercritical flow. Careful attention must be taken to prevent excessive oscillatory waves, which can extend down the entire length of the channel from only minor obstructions upstream. Imperfections at paved joints can cause rapid deterioration of the joints, which may cause a complete failure of the channel. In addition, high velocity flows at unintended cracks or joints create uplift forces by creating zones of flow separation with negative pressures which converts the velocity head to pressure head under the channel liner and can tear out concrete slabs and lesser liners. It is evident that when designing a lined channel with supercritical flow, the designer must use utmost care and consider all relevant factors.

In the City of Bella vista, all channels carrying supercritical flow shall be lined with continuously reinforced concrete linings, both longitudinally and laterally. The concrete linings must be protected from hydrostatic uplift forces from high water tables; momentary inflow behind the lining; and localized flooding. See Section 3.3.2 for concrete lining specifications. For supercritical flow, minor downstream obstructions do not create any backwater effect. Backwater computation methods are applicable for computing the water surface profile (see Section 3.1.6) or the energy gradient in channels having a supercritical flow. However, the computations must proceed in a downstream direction. The designer must take care to prevent the possibility of unanticipated hydraulic jumps forming in the channel. Design of a supercritical channel for a Froude number less than 1.2 will not be permitted by the City.

Roughness coefficients for lined channels are particularly important when dealing with supercritical flow. Once a particular roughness coefficient is chosen, the construction inspection must be carried out in a manner to insure that the particular roughness is obtained.

2.2 Preliminary Design Criteria

2.2.1 Design Velocity

Minimum and maximum velocities must be considered in the design of open channels. From structural and stability standpoints, maximum velocities are of concern. However, minimum velocities shall also be considered in design with respect to sediment accumulation and channel maintenance. For channels with high velocity flows, drop structures, suitable channel lining, check dams, and/or other velocity controls will need to control erosion and maintain channel stability. Froude number criteria also restrict velocity. *Subcritical* flow is desirable since the velocity for *subcritical* flow is less than that of critical or *supercritical* flow for a given discharge.

The flow velocity during the major design storm (i.e., 100-year) must recognize the scour potential of the channel, whether natural, grassed, bioengineered, rip-rapped or concrete-lined. Average velocities need to be determined using backwater calculations, which account for water draw-downs at drops, expansions, contractions and other structural controls. Velocities must be kept sufficiently low to prevent excessive erosion in the channel. As preliminary design criteria, flow velocities shall not exceed velocities and Froude numbers given in Table OC-1 and Table OC-4Table OC-4 for non-reinforced channel linings and, in general, shall not exceed 18 ft/sec for reinforced channel linings. Channel-specific velocity criteria depend greatly on the channel lining and slope and are presented in more detail in Section 3.0 of this chapter for various types of open channels.

Computer modeling software, such as HEC-RAS, shall be used to estimate maximum velocities for erosive or hazard considerations or localized scour in a channel. Computer modeling software shall be used to design/analyze primary channels while channel design spreadsheets associated with this *Manual* shall be used in the design of tertiary and secondary channels.

2.2.2 Design Depths

The maximum design depths of flow should also recognize the scour potential of the channel lining and the bank materials. Scouring power of water increases in proportion to the third to fifth power of flow depth and is also a function of the length of time that the flow is occurring (USBR 1984). As criteria, the design depth of flow shall not exceed 5.0 feet for the major storm runoff flow during a 100-year flood in areas of the channel cross section outside the low-flow channel area, and less depth is desirable for channel stability. Low-flow channel depth should be between 3.0 and 5.0 feet.

2.2.3 Design Slopes

2.2.3.1 Channel Slope

The slope of a channel affects flow velocity, depth, and regime and can have a significant impact on erosion and channel stability. Channel slope criteria vary based on the type of channel. However, the slope of a channel shall not be so steep as to result in a Froude number greater than 0.5 or 0.8 for the 100-year event depending on soil erodibility characteristics (see Table OC-1 through Table OC-7Table OC-7). For steep-gradient drainageways, drop structures are necessary to meet slope criteria. Design of drop structures is not specifically addressed in this *Manual*. Instead the design engineer is directed to FHWA's *Hydraulic Engineering Circular No. 14, 3rd Edition (HEC-14 2006)*, *Hydraulic Design of Energy Dissipators for Culverts and Channels*. An important consideration in channel slope is sinuosity of the channel - straightening of a natural channel inevitably results in an increase in slope. Conversely, for a constructed channel, a design which incorporates channel meanders can be used to satisfy slope criteria and potentially reduce the number of drop structures required.

2.2.3.2 Side Slopes

Channel banks with flatter the side slopes remain more stable. For grassed channels; channels with wetland bottoms; and bioengineered channels shall not have side slopes steeper than 3:1 horizontal-to-vertical. Channels that require minimal slope maintenance (such as concrete channels) may have side slopes as steep as 1.5:1, although public safety issues must be taken into account. For riprap-lined channels, side slopes shall not be steeper than 3:1. Rip-rap lined channels shall only be used upon approval by the City.

2.2.4 Curvature and Transitions

Generally, the gentler the flow centerline (called a thalweg) curves, the better the channel will function. Channel alignments should not be selected to maximize land-use opportunities for lot layout. Instead, lot layouts should be selected based on channel alignment. The thalweg curvature of the channel shall have a radius of at least 3 times the top width of the 100-year flow channel. The exception to this curvature requirement is for concrete channels that may experience *supercritical* flow conditions. From a practical standpoint, it is not advisable to have any curvature in a channel conveying *supercritical* flow, since minor disruptions can be amplified as they move downstream.

Super-elevation must also be considered with respect to curvature. Curves in a channel cause the flow velocity to be greater on the outside of the curve. Due to centrifugal force the depth of flow is greater on the outside of a curve. This rise in water surface on the outside of a curve is referred to as super-elevation. For *subcritical* flows, super-elevation can be estimated by:

$$\Delta y = \frac{V^2 * T}{2 * g * r_c}$$ **(Equation OC-9)**

in which:

Δy = Increase in water surface elevation above average elevation due to super-elevation (ft)

V = Mean flow velocity (ft/sec)

T = Channel top width at the water surface under design flow conditions (ft)

g = Gravitational constant (32.2 ft/sec^2)

r_c = Radius of curvature (ft)

Furthermore, transitions (expansions and contractions) are addressed in Section 3.4.2.6 (riprap-lined channels) and in Chapter 8 – *Culvert / Bridge Hydraulic Design*.

2.2.5 Design Discharge Freeboard

Residual discharge freeboard is necessary to ensure that a design developed using idealized equations will perform as desired under actual conditions. The amount of residual freeboard that must be allowed depends on the type of channel and the location and elevation of structures adjacent to the channel. Preserving existing floodplains maximizes “natural” freeboard. Freeboard requirements are addressed for specific channel types in Section 3.0 of this chapter. The height of freeboard shall be a minimum of 1-foot for velocities up to 5-fps; 2-foot for velocities over 5-fps; or provide additional capacity of at least one-third of the design flow.

2.2.6 Erosion Control

For major drainage channels, protection against erosion is key to maintaining channel stability. Unless hard-lined and vigilantly maintained, most major drainage channels are susceptible to at least some degree of erosion. The concave outer banks of stream bends are especially susceptible to erosion and may require armoring with riprap for grassed, bioengineered, or wetland bottom channels. High sediment loads to a channel may occur as a result of active construction in the watershed. Once an area is fully urbanized, the channel behavior will change. Flows increase significantly due to the increase in imperviousness in the watershed, and the runoff from these fully urbanized areas contains relatively low levels of sediment. As a result, the potential for erosion in the channel increases.

In the Bella Vista area, most waterways will need the construction of drops (see HEC-14 2006) and/or erosion cutoff check structures to control the channel slope. Typically, these grade control structures are spaced to limit channel degradation to what is expected to be the final stable longitudinal slope after full urbanization of the tributary watershed. Designers should also be aware of the erosion potential created by constriction and poorly vegetated areas. An example is a bridge crossing over a grassed major drainage channel; where velocities increase as a result of the constriction created by the bridge; and bank cover is poor due to the inability of grass to grow in the shade of the bridge. In such a situation, structural stabilization is needed.

Another aspect of erosion control for major drainage channels is controlling erosion during and after construction of channel improvements. Construction of channel improvements during times in the year that are typically drier can reduce the risk of erosion from storm runoff. Temporary stabilization measures including seeding, mulching, and erosion controls (such as installation and maintenance of silt fencing) shall be used during construction of major drainage improvements to minimize erosion. Refer to Chapter 9 – *Construction Site Stormwater Management* for additional erosion control ideas for open channels.

2.2.7 Utility Proximity

It is important to consider the location and depth of utilities near open channels. Utilities that are too close linearly and/or too shallow when crossing a channel pose future maintenance problems along with future planning issues. Keeping utilities out of the general operating plane of open channels allows the entity maintaining and operating the channel more flexibility when it comes to dredging, repairing, widening, or other improvements/maintenance. For this reason, all channels within the City do not allow utilities between the top of banks except for crossings perpendicular to centerline of the channel and must be a minimum of 3-feet deep. Furthermore, no utilities are allowed between the maintenance road's stable surface and top of bank. By implementing these proximity requirements between open channels and utilities, the City hopes to prevent costly conflicts between open channels and utilities in the future.

2.3 Choice of Channel Type and Alignment

2.3.1 Types of Channels for Major Drainageways

The types of major drainage channels available to the designer are almost infinite. Selection of a channel type depends upon applying good hydraulic practice, environmental design, sociological impact, and basic project requirements. However, from a practical standpoint, it is useful to identify general types of channels that can be used by the designer as starting points in the design process. The following types of channels may serve as major drainage channels for the 100-year runoff event in urban areas:

<u>Natural Channels</u>—Natural channels are drainageways carved or shaped by nature before urbanization occurs. They often, but not always, have mild slopes and are reasonably stable. As the channel's tributary watershed urbanizes, natural channels often experience erosion and degrade. As a result, they require grade control checks and stabilization measures.

Grass-Lined Channels—Among various types of constructed or modified drainageways, grass-lined channels are some of the most frequently used and desirable channel types. They provide channel storage, lower velocities, and various multiple use benefits. Grass-lined channels in urbanizing watersheds shall be stabilized with grade control structures to prevent down-cutting; depression of the water table; and degradation of natural vegetation. Certain flow areas may need to be armored or otherwise stabilized to guard against erosion.

Composite Channels—Composite channels have a distinct low-flow channel that is vegetated with a mixture of wetland and riparian species. A monoculture of vegetation shall be avoided. In composite channels, dry weather (base) flows are encouraged to meander from one side of the low-flow channel to the other. The low-flow channel banks need heavy-duty bio-stabilization that includes rock lining to protect against undermining and bank erosion.

Concrete-Lined Channels—Concrete-lined channels are high velocity artificial drainageways that are not recommended for use in urban areas. The use of this channel type requires City approval. However, in retrofit situations where existing flooding problems need to be solved and where right-of-way is limited, concrete channels can offer advantages over other types of open drainageways.

Reinforced-Lined Channels (Riprap and TRMs)—Riprap-lined channels offer a compromise between grass-lined channels and concrete-lined channels. Riprap-lined channels can somewhat reduce right-of-way needs relative to grass-lined channels and can handle higher velocities and greater depths than grass-lined channels. Relative to concrete-lined channels, velocities in riprap-lined channels are generally not as high. Riprap-lined channels are more difficult to keep clean and maintain than other types of channels and are recommended for consideration only in retrofit situations where existing urban flooding problems are being addressed. The use of this channel type is discouraged and requires City approval. A more desirable alternative to the use of riprap would be substituting turf reinforcement mats (TRMs) in place of riprap. This method is encouraged by the City when the use of such TRMs when adhering to the manufacturers recommended application. Refer to the EPA's *Storm Water Technology Fact Sheet – Turf Reinforcement Mats* document (http://www.epa.gov/ – EPA 832-F-99-002) for more information concerning the employment of TRMs.

Bioengineered Channels—Bioengineered channels utilize vegetative components and other natural materials in combination with structural measures to stabilize existing channels in existing urban areas; areas undergoing urbanization; and to construct natural-like channels that are stable and resistant to erosion. Bioengineered channels provide channel storage, slower velocities, and various multiple use benefits.

2.3.2 Factors to Consider in Selection of Channel Type and Alignment

The choice of channel type and alignment must be based upon a variety of multi-disciplinary factors and complex considerations that include, among others:

Hydraulic Considerations

- Slope of thalweg
- Right-of-way
- Capacity needs
- Basin sediment yield
- Topography
- Ability to drain adjacent lands

Structural Considerations

- Cost
- Availability of material
- Areas for wasting fill
- Seepage and uplift forces
- Shear stresses
- Pressures and/or fluctuations
- Momentum transfer

Environmental Considerations

- Neighborhood character
- Neighborhood aesthetic requirements
- Street and traffic patterns
- City and/or county policies
- Need for new green areas
- Wetland mitigation
- Character of existing channel
- Wildlife habitat
- Water quality enhancement

Sociological Considerations

- Neighborhood social patterns
- Neighborhood children population
- Public safety of proposed facilities for storm and non-storm conditions
- Pedestrian traffic
- Recreational needs
- Right-of-way corridor needs

Maintenance Considerations

- Life expectancy
- Repair and reconstruction needs
- Maintainability
- Proven performance
- Accessibility
- Regulatory constraints to maintenance

2.3.3 Summary of Design Criteria

Material selection must also be able to perform under the anticipated conditions of the channel. The following tables provide a summary of applicable design criteria/performance thresholds for each material type.

Table OC-3: Grass-Lined Open Channel Design Criteria

Use of channel type subject to City approval?	No
Maximum Normal Depth Velocity (ft/sec)	≤ 5-fps for 100-year design
Manning's *n* – Used to check channel capacity (flow depth)	0.040 (or see Section 3.1.3, Figure OC-4 Retardance Class C)
Manning's *n* – Used to check maximum velocity (channel stability)	0.030 (or see Section 3.1.3, Figure OC-4 Retardance Class D)
Froude Number [3]	< 0.8
Longitudinal Channel Slope [1]	≥ 0.75%
	≥ 1.00% if no trickle channel is present
Side Slopes (max.)	3H:1V
Channel Bottom Width (trapezoidal)	≥ 5-ft
Channel Bottom Cross-slope	1% to 2%
Centerline Curve Radius (feet) (subcritical flow)	≥ 3x the top width of the 100-year design storm
Centerline Curve Radius (supercritical flow)	Supercritical Flow NOT ALLOWED
Channel Bend Protection	Section 3.1.5.1
Outfall Height Above Channel Invert (feet)	≥ 1-ft (with properly designed outlet protection)
Normal Depth (feet) outside of the trickle/low-flow channel	≤ 5-ft at 100-year design peak flow for fully developed watershed
Secondary Channels Freeboard [2]	≥ 1-ft
Primary Channels Freeboard [2]	≥ 2-ft
Trickle Channel (if any) sized for …	2.0% of 100-year design peak flow for fully developed watershed
Trickle Channel (if any) Bottom Width	≥ 5-ft
Low-flow Channel sized for …	5-year design peak flow for fully developed watershed
Low-flow Channel Bottom Width	≥ 5-ft
Low-flow Channel Depth	≥ 3.0-ft and ≤ 5.0-ft
Maintenance Access Road for *Primary Channels*	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures
Maintenance access locations from city streets or drainage easements…	Locations to be determined during the review process.
Drop downstream of each culvert or bridge crossing	Section 3.2.2
Secondary Channels water surface profile shall be computed for…	1-, 10-, 25-, and 100-year storm events
Primary Channels water surface profile shall be computed for…	1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events
Utility location and depth near channels	Not allowed between the top of banks except for crossings which must be ≥ 3-ft deep.
	Not allowed between maintenance road stable surface and top of bank.

[1] Maximum channel slope controlled by maximum channel velocity.

[2] Super-elevation must be added in curves/bends – See Section 2.2.4.

[3] Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

Table OC-4: Composite Open Channel Design Criteria

Use of channel type subject to City approval?	No
Maximum Normal Depth Velocity (ft/sec)	≤ 5-fps for 100-year design
Manning's *n* – Used to check maximum velocity (channel stability)	See Section 3.2.1, Figure OC-4 (Retardance Curve D), Table OC-8
Manning's *n* – Used to check channel capacity (flow depth)	See Section 3.2.1, Figure OC-4 (Retardance Curve C), Table OC-8
Composite Manning's *n* calculated for channel and used in hydraulic computations	See Section 3.2.2, Equation OC-11
Froude Number[3]	< 0.8
Longitudinal Channel Slope[1]	Base on "new channel" roughness condition. See Section 3.2; ≥ 0.25%
Side Slopes (max.) in low-flow channel…	2.5H:1V [TRM (preferred) or soil riprap (requires approval) reinforcement required]
Side Slopes (max.) above low-flow channel…	3H:1V (grass-lined)
Channel Bottom Width	≥ 5-ft
Channel Bottom Cross-slope	"Flat bottom"
Centerline Curve Radius (feet) (subcritical flow)	≥ 3x the top width of the 100-year design storm
Centerline Curve Radius (supercritical flow)	Supercritical Flow ***NOT ALLOWED***
Channel Bend Protection	See Section 3.1.5.1
Outfall Height Above Channel Invert (feet)	≥ 2-ft
Normal Depth (feet) outside of the trickle/low-flow channel	≤ 5-ft at 100-year design peak flow for fully developed watershed
Secondary Channel Freeboard[2]	≥ 1-ft
Primary Channel Freeboard[2]	≥ 2-ft
Low-flow Channel sized for …	5-year design peak flow for fully developed watershed
Low-flow Channel depth (feet)	Between 3.0 and 5.0 feet
Maintenance Access Road	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures
Maintenance access locations from city streets or drainage easements…	Locations to be determined during the review process.
Water surface profile shall be computed for…	10-year and 100-year storm events
Drop downstream of each culvert or bridge crossing	See Section 3.2.3
Secondary Channels water surface profile shall be computed for…	1-, 10-, 25-, and 100-year storm events
Primary Channels water surface profile shall be computed for…	1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events
Utility location and depth near channels	Not allowed between the top of banks except for crossings which must be ≥ 3-ft deep.
	Not allowed between maintenance road stable surface and top of bank.

[1] Maximum channel slope controlled by maximum channel velocity.

[2] Super-elevation must be added in curves/bends – See Section 2.2.4.

[3] Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

Table OC-5: Concrete-Lined Open Channel Design Criteria

Use of channel type subject to City approval?	Yes
Maximum Normal Depth Velocity (ft/sec)	≤ 18-fps for 100-year design
Manning's *n* – Used to check maximum velocity and Froude Number ≤ 0.7	0.011
Manning's *n* – Used to check channel capacity and Froude Number ≥ 1.4	0.013
Froude Number [5]	≤ 0.7 [3] and ≥ 1.4 [4] under both Manning's *n*
Longitudinal Channel Slope [1]	≤ 1.00%
Side Slopes (max.)	1.5H:1V (unless structurally designed for steeper slope)
Channel Bottom Width (feet)	≥ 5-ft
Centerline Curve Radius (subcritical flow)	≥ 3x the top width for the 100-year design storm
Centerline Curve Radius (supercritical flow)	No curvature permitted
Concrete channel lining thickness (inches)	≥ 5-in when F_r ≤ 0.7 [3] ; ≥ 8-in when F_r ≥ 1.4 [4]
Outfall Height Above Channel Invert (feet)	≥ 1-ft
Secondary Channels Freeboard [2]	≥ 1-ft See Section 3.3.1.4
Primary Channels Freeboard [2]	≥ 2-ft See Section 3.3.1.4
Maintenance Access Road	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures
Maintenance access locations from city streets or drainage easements…	Locations to be determined during the review process.
Secondary Channels water surface profile shall be computed for…	1-, 10-, 25-, and 100-year storm events
Primary Channels water surface profile shall be computed for…	1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events
Safety Requirements	6-ft fence/barrier required in areas where channel depth is ≥ 3-ft
Utility location and depth near channels	Not allowed between the top of banks except for crossings which must be ≥ 3-ft deep.
	Not allowed between maintenance road stable surface and top of bank.

[1] Minimum channel slope controlled by minimum channel cleaning velocity (3-fps) during low-flows.

[2] Super-elevation must be added in curves/bends – See Section 2.2.4.

[3] Requires free draining granular bedding under channel cover at 6-inch minimum thickness.

[4] Requires free draining granular bedding under channel cover at 9-inch minimum thickness.

[5] Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

Table OC-6: Riprap-Lined Open Channel Design Criteria

Use of channel type subject to City approval?	Yes
Maximum Normal Depth Velocity (ft/sec)	≤ 12-fps
Manning's *n* – Used to check maximum velocity (channel stability)	0.030
Manning's *n* – Used to check channel capacity (flow depth)	0.041
Froude Number [1]	≤ 0.8
Side Slopes (max.)	2.5H:1V
Use of soil riprap …	Section 3.1.5.2; Figure OC-5; Section 3.4.1.1
Rock specific gravity and other rock parameters	≥ 2.50 and see Section 3.4.1.1
Riprap rock size / gradation	Sizing – Equation OC-13 and Table OC-14
	Gradation – Table OC-11 & Table OC-12
Riprap blanket thickness	≥ 2x d_{50} in normal channel
	≥ 3x d_{50} for at least 3-ft upstream and downstream ends of lining
Toe protection provided according to…	Section 3.4.2.4 & Figure OC-10
Centerline Curve Radius (subcritical flow)	≥ 3x the top width of the 100-year design storm
Centerline Curve Radius (supercritical flow)	Supercritical Flow NOT ALLOWED
Channel Bend Protection – Riprap sizing…	Size riprap in bends according to Section 3.4.2.5. Use Equation OC-13 and Table OC-14 based on the adjusted velocity (V_a) from Equation OC-10.
Channel Bend Protection – Riprap extents…	Extend downstream of bend ≥ 2x the top width of the 100-year design storm.
Outfall Height Above Channel Invert (feet)	≥ 1-ft
Secondary Channels Freeboard [2]	≥ 1-ft See Section 3.3.1.4
Primary Channels Freeboard [2]	≥ 2-ft See Section 3.3.1.4
Riprap at transitions – Riprap sizing …	Use Table OC-14 by using ≥ 1.25x maximum velocity in transition.
Riprap at transition – Riprap extents …	Extend upstream by 5-ft and downstream by ≥5x design flow depth.
Granular bedding – Gradation…	See Section 3.4.4.1; Table OC-15
Granular bedding – Thickness…	See Section 3.4.4.1; Table OC-16
Maintenance Access Road	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structure
Maintenance access locations from city streets or drainage easements…	Locations to be determined during the review process.
Secondary Channels water surface profile shall be computed for…	1-, 10-, 25-, and 100-year storm events
Primary Channels water surface profile shall be computed for…	1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events
Utility location and depth near channels	Not allowed between the top of banks except for crossings which must be ≥ 3-ft deep.
	Not allowed between maintenance road stable surface and top of bank.

[1] Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

[2] Super-elevation must be added in curves/bends – See Section 2.2.4.

Table OC-7: Bioengineered Open Channel Design Criteria

Use of channel type subject to City approval?	Yes
Maximum Normal Depth Velocity (ft/sec)	≤ 2-fps for 5-year design
	≤ 4-fps for 100-year design
Froude Number [2]	0.3 for 5-year design
	0.3 for 100-year design
Longitudinal Channel Slope [1]	≤ 0.20%
Centerline Curve Radius (feet) (subcritical flow)	≥ 3x the top width of the 100-year design storm
Centerline Curve Radius (supercritical flow)	Supercritical Flow NOT ALLOWED
Design guidelines	Section 3.5.7
Utility location and depth near channels	Not allowed between the top of banks except for crossings which must be ≥ 3-ft deep.
	Not allowed between maintenance road stable surface and top of bank.

[1] Maximum channel slope controlled by maximum channel velocity.

[2] Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

2.3.4 Environmental Permitting Issues

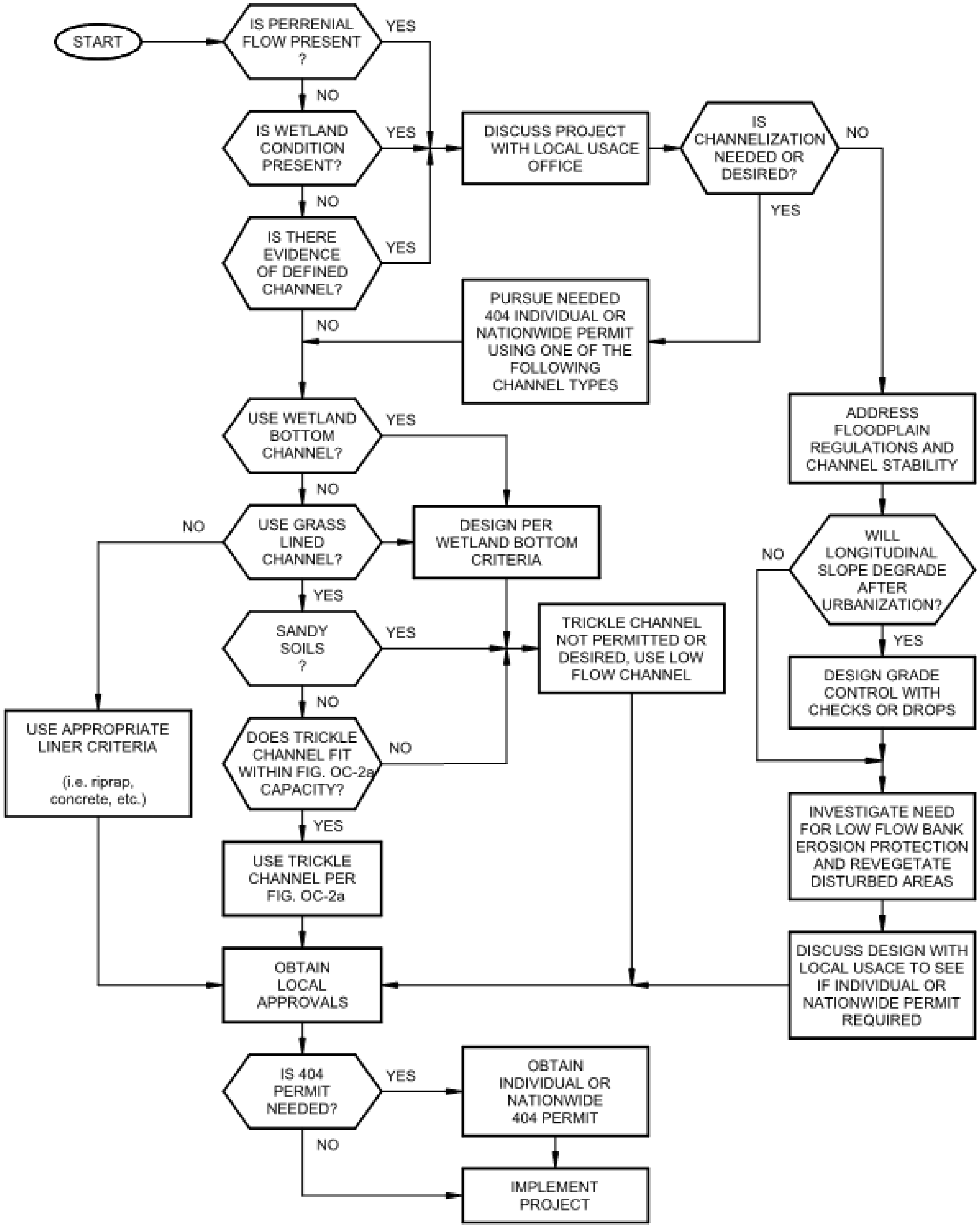
Environmental permitting, in particular wetland permitting, must be considered in selection of the type of major drainage channel. To assist with the selection of the type of open channel improvements to be used where environmental permitting is concerned, a flow chart is presented in Figure OC-2. The flow chart contains a series of questions to be considered in light of the requirements in this *Manual* and the requirements of the Clean Water Act (CWA); Section 404 (dredge and fill in jurisdictional wetlands and “Waters of the United States”).

Along with the chart, the first step is to determine whether channelization is needed or desired. In many cases, a well-established natural drainageway and its associated floodplain could be preserved and protected from erosion damage. Therefore, before deciding to channelize, assess whether the value of reclaimed lands will justify the cost of channelization and whether a new channel will provide greater community and environmental benefits than the existing drainageway.

If the decision is to neither channelize nor re-channelize an existing drainageway, then investigate the stability of the natural drainageway and its banks; design measures to stabilize the longitudinal grade and banks as needed in selected areas; and obtain necessary Section 404 permits and other approvals for these improvements. The designer should review the requirements for natural channels to ensure any channel improvements meet the City’s requirements.

If the decision is made to channelize, then determine whether the existing natural drainageway has a perennial flow; evidence of wetland vegetation; and/or is a well-established intermittent channel. This will often require the assistance of a biologist with wetland training. If any of these conditions exist, then the project is likely to be subject to individual or nationwide Section 404 permitting requirements. Regardless, it is suggested the designer check with the local USACE office early in the design process to determine which permit(s) will be needed. Keep in mind that it is the responsibility of the applicant to comply with all applicable federal and state laws and regulations. Approvals by the local authorities do not supersede or waive compliance with these federal laws.

Figure OC-2: Flow Chart for Selecting Channel Type and Assessing the Need for a Section 404 Permit (UDFCD USDCM 2002)



2.3.5 Maintenance

All drainage channels in urban areas require periodic maintenance to ensure they are capable of conveying their design flow and to ensure that channels do not become a public nuisance and eyesore. Routine maintenance (i.e. mowing for weed control or seasonal clean-outs); inspections; special unscheduled maintenance (i.e. clean-out after large events); and restorative maintenance are expected to preserve operation of the channels.

A maintenance access road with a minimum passage width of 12-feet shall be provided along the entire length of all major drainageways except at drop structures, where a 20-foot maintenance road is needed. Maintenance roads shall consist of a 10-foot (minimum) wide stable surface consisting of a typical section directed by the City. This typical section will be determined during the design review process.

Furthermore, it will be necessary to consider the location and implementation of maintenance accesses along drainage easements and where open channels intersect city streets. The purpose of a maintenance access will be to serve City maintenance vehicles a definitive and convenient access directly into an open channel. Maintenance accesses may be something as simple as providing an embankment slope flatter than required for the specific channel type for which access is desired. Or it could include the detailed construction of a permanent heavy-duty pavement to provide access for more substantial equipment into the channel. Decisions about the locations and type of these accesses will be determined by the City during the planning and review process.

Further discussion defining the party responsible for maintaining a specific type of open channel is discussed in Section 2.5.

2.4 Design Flows

Open channels must be able to convey the flow from a fully urbanized watershed for the design considerations outlined here. Methods for calculating the flow from a fully urbanized watershed are described in Chapter 4 – *Determination of Stormwater Runoff*. A channel's lining, geometry (depth, width, alignment, etc.), and freeboard characteristics shall be designed in relation to the channel's maintenance classification as defined in Section 2.5 of this chapter. Channels shall be designed according to the following design storm frequencies as follows:

- Primary Channel – 100-year design storm with more than 24-inches of freeboard
- Secondary Channel – 50-year design storm with more than 12-inches of freeboard
- Tertiary Channel – 10-year design storm

Furthermore, open channels with a residual floodplain must be able to convey the flow from a fully urbanized watershed for the event with a 100-year recurrence interval without significant damage to the system. In addition to the capacity consideration of the 100-year event, the designer must also consider events of lesser magnitudes. For the low-flow channel of any type, a 5-year storm peak discharge for fully developed conditions is to be used for its design. Base flow must also be assessed, especially for grassed channels; channels with wetland bottoms; and bioengineered channels. Base flows are best estimated by examining already-urbanized watersheds that are similar to the planned urban area in terms of imperviousness, land use, and hydrology.

2.5 Maintenance Classification – Primary Channels, Secondary Channels, and Tertiary Channels

In order for open channels to function according to their original design, channels require periodic maintenance and repair. Maintenance and repair includes removal of debris and litter from the channel; regular mowing of grass-lined and composite channels to maintain expected channel roughness; repair and stabilization of eroded channel banks/bottoms; repair/replacement of any erosion control structures (including but not limited to channel drop structures, armored channel lining, etc.); and/or any other necessary upkeep work within the established open channel boundaries that don’t reflect the channels intended purpose.

Since open channels provide a benefit to a number of different users, the City has established certain physical and operational criteria that designate channels as either primary, secondary, or tertiary. The definitions below along with Table OC-8 describe the use, maintenance/repair responsibilities, and designation criteria of each category of the channels.

- Primary Channel: A major open channel that serves as a primary waterway to conduct runoff generated in a large composite area (typically more than 30-acres). More so, any channel that has a mapped flood zone (floodway, floodplain, etc.) as determined and/or studied by the City or FEMA. Runoff conducted by primary channels is collected in the channel from discharges of a watershed, closed storm sewer systems, secondary and tertiary channels, and from the convergence of other primary channels. These types of channels are to be primarily maintained by the City and should be placed in a dedicated drainage easement.
- Secondary Channel: A moderate open channel that collects runoff from storm sewer systems, tertiary and other secondary channels, and feeds into a primary channel. Drainage areas for secondary channels typically range from between 2 and 30 acres. These types of channels are to be primarily maintained by a Property Owner Association (POA); developer of the subdivision; or other responsible entity for a development and should be placed in a dedicated drainage easement.
- Tertiary Channel: A small minor channel that serves as a conduit to channel runoff (typically less than 2 acres). These types of channels are to be maintained by the owner(s) of the property it serves. Maintenance responsibilities for the property owner end at the furthest point upstream

and/or downstream the channel exists within the property's legal recorded boundaries. These channels are not typically placed in a drainage easement.

Table OC-8: Open Channel Maintenance Classification Physical Criteria[5]

Channel Designation	Maintenance/Repair Responsibility Assigned to …	Channel Criteria for Design Event
Primary	City (Primary Channels TO BE DEEDED to the CITY)	≥ 2-foot flow depth [1] & ≥ 10-foot bottom width [1]
Secondary	POA, developer	≥ 1-foot flow depth [2] & ≥ 5-foot bottom width [2] or ≥ 1.5-foot flow depth [3] & ≥ 10-foot top width of flow [3]
Tertiary	Property owner / homeowner	≤ 1-foot flow depth [4] or ≤ 10-foot top width of flow [4]

[1] Channel criteria based on a trapezoidal ditch, 3:1 side slopes, 10-foot bottom width, 0.50% longitudinal slope, n=0.040, 10-min T_c with intensity from 10-yr. design storm, 30-acre drainage area.

[2] Channel criteria based on a trapezoidal ditch, 3:1 side slopes, 5-foot bottom width, 0.50% longitudinal slope, n=0.040, 10-min T_c with intensity from 10-yr. design storm, 4-acre drainage area.

[3] Channel criteria based on a typical v-bottom ditch, 3:1 side slopes, 0.50% longitudinal slope, n=0.040, 10-min T_c with intensity from 10-yr. design storm, 4-acre drainage area.

[4] Channel criteria based on a typical v-bottom ditch, 5:1 side slopes, 0.50% longitudinal slope, n=0.040, 10-min T_c with intensity from 10-yr. design storm, 4-acre drainage area.

[5] The criterion presented does not address every kind of channel type possible within the City. Instead the listed criteria provide an approximate basis from which to evaluate the maintenance classification of channel that is either under design or already in use. The City will make the final determination of channel classification.

Backwater analysis computer modeling software, such as HEC-RAS, shall be used to design/analyze primary channels while channel designs associated with this *Manual* shall be used in the design of tertiary and secondary channels.

3.0 OPEN-CHANNEL DESIGN CRITERIA

The purpose of this section is to provide design criteria for open channels, including grass-lined channels, composite channels, concrete-lined channels, riprap-lined channels, bioengineered channels, and natural channels. Open-channel hydraulic principles summarized in Section 2.0 can be applied using these design criteria to determine channel geometry and hydraulics.

3.1 Grass-Lined Channels

Grass-lined channels are considered by the City to be the most desirable type of artificial channels for new development(s) where natural channels are absent or have limited environmental value. Channel storage, lower velocities, and aesthetic and recreational benefits create advantages over other channel types.

3.1.1 Design Criteria

Figure OC-4, Figure OC-5, and Figure OC-6 provide useful representative sketches for grass-lined channels showing the acceptable design criteria for grass-lined channels.

3.1.1.1 Design Velocity and Froude number

In determining flow velocity during the major design storm (100-year event), the designer must recognize the scour potential of the soil-vegetative cover complex. Average velocities need to be determined using backwater calculations, which account for water draw-down at drops, expansions, contractions, and other structural controls. Velocities must be kept sufficiently low to prevent excessive erosion in the channel. The maximum normal depth velocities and Froude numbers for 100-year flows in a grass-lined channel are listed in Table OC-1.

3.1.1.2 Design Depths

The maximum design depths of flow should recognize the scour potential of the soil-vegetative cover complex. The scouring power of water increases in proportion to a third to a fifth power of depth of flow and is a function of the length of time the flow is occurring. As preliminary criteria, the design depth of flow for the major storm runoff flow shall not exceed 5.0-feet in areas of the channel cross section outside the low-flow or trickle channel area. Normal water depth can be calculated using Manning's Equation from Section 2.1.1 of this chapter.

3.1.1.3 Design Slopes

To function without instability, grass-lined channels normally have longitudinal slopes greater than or equal to 0.75%. Where the natural slope becomes steep enough to cause velocities in excess of those in Table OC-1 for grass-lined channels, drop structures shall be utilized.

With respect to side slopes, the flatter the side slope, the more stable it is. For grassed channels, side slopes shall not be steeper than 3H:1V.

3.1.1.4 Curvature

The more gently a thalweg curves, the better the channel will function. At a minimum, thalweg curves shall have a radius that is equal to or greater than 3 times the top width (*T*) of the 100-year design flow (or other major flow) in the channel.

3.1.1.5 Design Discharge Freeboard

Bridge deck bottoms and sanitary sewers (culvert tops, etc.) often control the freeboard along the channel in urban areas. Where such constraints do not control the freeboard, the allowance for freeboard shall be determined by the conditions adjacent to the channel. For instance, localized overflow in certain areas may be acceptable and may provide flow storage benefits. In general, a minimum freeboard of 12 inches (or 24 inches as directed by the City) shall be required between the water surface and top of bank. Along major streams such as Little Sugar Creek, Tanyard Creek, Spanker Creek, Gordon Hollow Creek, Pinton Hollow Creek and others determined by the City where potential for downed trees and other debris exists during a flood, a 24 inches of freeboard is required for the 100-year design flow.

For curves in the channel, super-elevation shall be evaluated using Equation OC-9 in Section 2.2.4 and shall be included in addition to freeboard.

3.1.2 Channel Cross Sections

The channel shape may be almost any type suitable to the location and environmental conditions. Often the shape can be chosen to suit open space and recreational needs; to create wildlife habitat; and/or to create additional sociological benefits (Murphy 1971). Typical cross sections suitable for grass-lined channels are shown in Figure OC-4.

3.1.2.1 Bottom Width

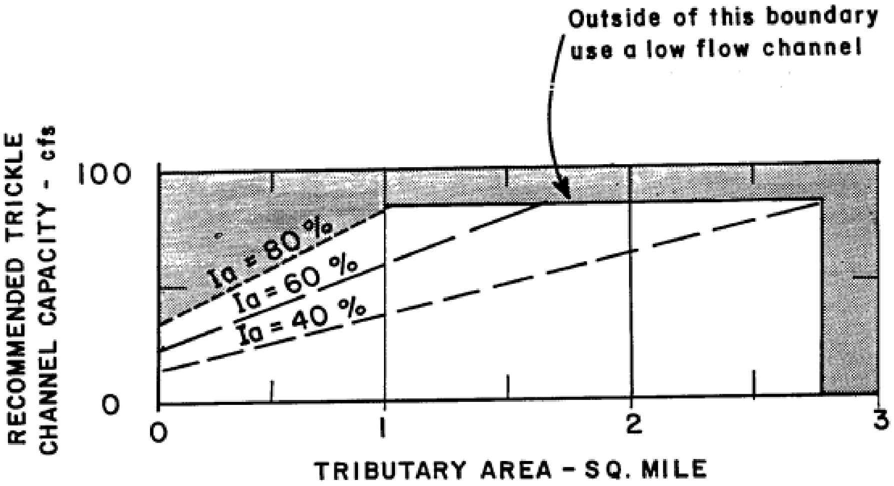
The bottom width should be designed to satisfy the hydraulic capacity of the cross section while recognizing the limitations on velocity; depth; and Froude number. For a given discharge, the bottom width can be calculated using the depth, velocity, and Froude number constraints in Section 3.1.1.1 and Section 3.1.1.2 using Equation OC-2 from Section 2.1.1 of this chapter.

3.1.2.2 Trickle and Low-Flow Channels

When base flow is present or is anticipated as the drainage area develops, a trickle or low-flow channel is required. Steady base flow will affect the growth of grass in the bottom of the channel, create maintenance needs, and can cause erosion. The purpose of a trickle channel is to convey very small perennial flows in a localized section of the overall channel to prevent adverse maintenance and erosion conditions. A trickle channel is a defined (typically narrow) longitudinal channel located at the thalweg of the overall channel and is used to transport steady base flows, typically ≤ 1-ft depth. Steady base flows that would be typical of a trickle channel would be runoff from lawn irrigation, groundwater inflow into the channel, etc. Figure OC-4 should be used to estimate the required capacity of a trickle channel based on the percent of impervious area, I_a.

A low-flow channel serves two essential purposes. One purpose of a low-flow channel would be that of a trickle channel, just on a larger scale. Should a channel have a steady base flow that exceeds the limits set forth in Figure OC-4, a low-flow channel having stabilized banks must be used in place of a trickle channel. Secondly, a low-flow channel is designed to carry stormwater runoff conveyed in the channel during smaller and more common design storm events. A low-flow channel is designed to flow full at a depth less than 5-feet. More specific sizing and design criteria for low-flow/trickle channels are presented in Section 3.1.4 of this chapter.

Figure OC-3: Minimum Capacity Requirements for Trickle Channel
(UDFCD USDCM 2002)



Note: I_a = tributary basin impervious area percentage using full basin development condition

3.1.2.3 Outfalls into Channel

Outfalls into grass-lined, major channels shall be at least 12 inches above the channel invert with adequate erosion protection provided at the outlet.

3.1.3 Roughness Coefficients

Designers shall use 0.040 and 0.030 for Manning's roughness coefficients, n, for grass-lined channels when checking design channel capacity (flow depth) and design maximum velocity (channel stability), respectively. In addition to these two set Manning's n, the designer is allowed to determine project specific roughness coefficients for grass-lined channels. Project specific roughness coefficients for grass-lined channels shall be determined based upon the product of the velocity and the hydraulic radius for different vegetative retardance classes (see Figure OC-4). When using the retardance curves for grass-lined channels, use Retardance C for finding Manning's n for determining channel capacity (depth) in a mature channel and Retardance D for finding the controlling velocity in a newly constructed channel to determine stability. The designer is referenced to *SCS Technical Paper No. 61 – Handbook of Channel Design for*

Soil and Water Conservation and FHWA's *Hydraulic Engineering Circular No. 15, 3rd Edition (HEC-15 2005)* for additional information concerning the background and development of the retardance curves in Figure OC-4.

3.1.4 Trickle and Low-Flow Channels

The low flows and present base flows from urban areas must be given specific attention. Waterways which are normally dry prior to urbanization will often have a continuous base flow after urbanization, both from overland and groundwater inflow. Continuous flow over grass or what used to be intermittent waterways will cause the channel profile to degrade; its cross-section to widen; its meanders to increase; destroy a healthy grass stand; and may create boggy nuisance conditions.

A trickle channel with a porous bottom (i.e. unlined) or a low-flow channel is required for all urban grass-lined channels. In some cases, a traditional concrete trickle channel may be necessary, but should be limited to headland tributary channels created in areas where no natural channel previously existed. However, low-flow/trickle channels with natural-like linings are preferable. Trickle channels with natural-like linings offer an advantage over concrete-lined trickle channels because they more closely mimic natural channels; have greater aesthetic appeal; provide habitat benefits; and provide vegetative diversity. These linings are best when porous and allow surfaces waters to reach the adjacent groundwater table while irrigating vegetation along the channel. In addition, a vegetated low-flow channel provides a degree of water quality treatment - unlike concrete lined channels that tend to flush pollutants accumulated on the impervious lining downstream during runoff events.

Steady base and/or low flows must be carried in a trickle channel or a low-flow channel. Trickle channels are to be used to pass constant base flows from groundwater, irrigation, or other constant sources of water runoff. The capacity of a trickle channel shall be 2.0% of the major (100-year storm) design flow for the fully developed condition, assuming no upstream detention. Low-flow channels shall be used for larger major drainageways, streams, and rivers and for channels located on sandy soils. A low-flow channel shall have a minimum capacity of passing the 5-year storm peak flow under the fully developed watershed conditions, assuming no upstream detention. To the extent practicable, a low-flow channel shall be gently sloped and shallow to promote flow through the channel's vegetation. See Figure OC-7 and Figure OC-8 for typical details of grass-lined channels with trickle and low-flow channels.

Using a soil-riprap mix for the low-flow channel lining can provide a stable, vegetated low-flow channel for grass-lined wetland bottom and bioengineered channels. Soil and riprap shall be mixed prior to placement for these low-flow channels. Soil-riprap low-flow channels shall have a cross slope of 1% to 2%. Its longitudinal slope shall be consistent with the channel type used.

Figure OC-4: Manning's *n* vs. *VR* for Two Retardances in Grass-Lined Channels
(taken from SCS-TP-61 Rev. 1954)

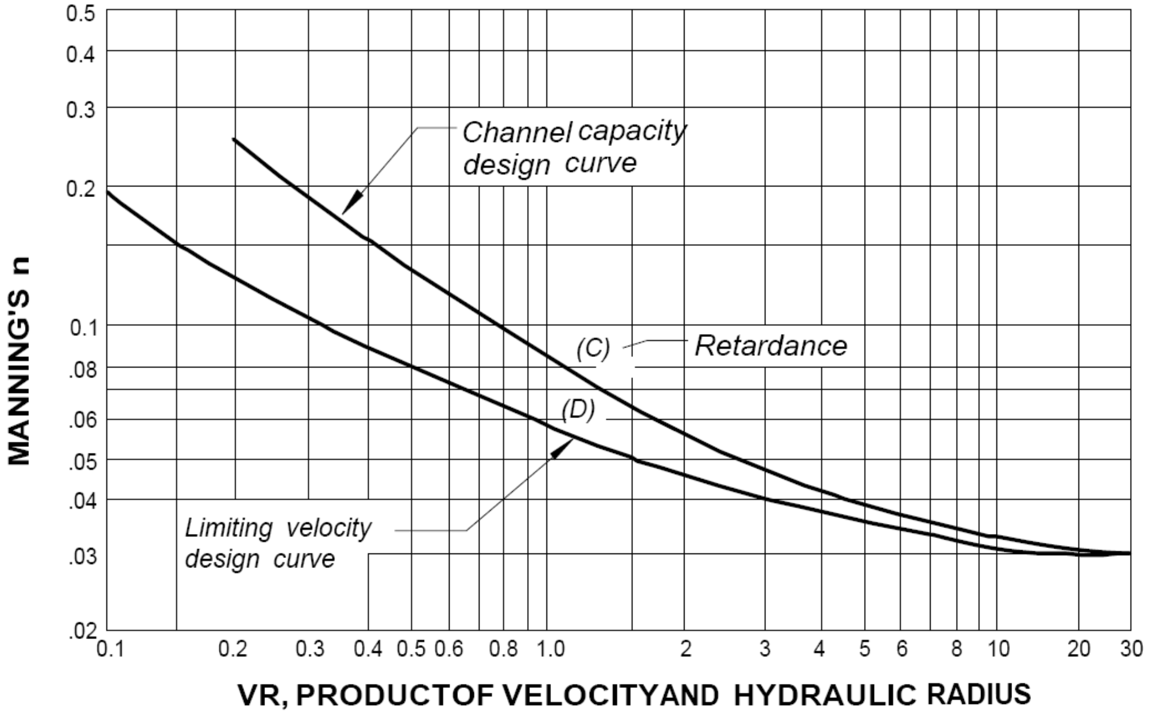
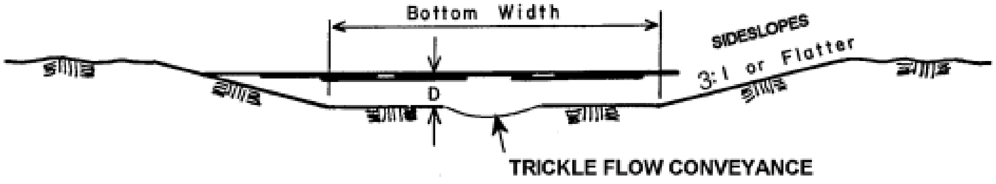
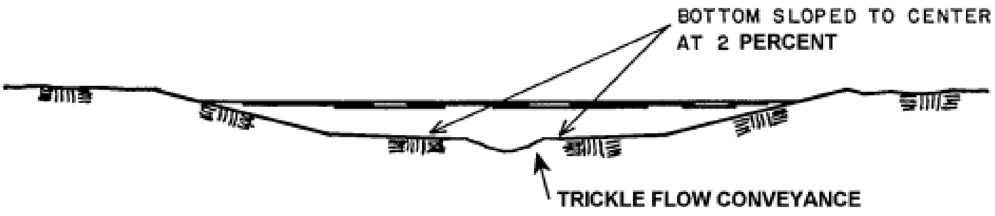


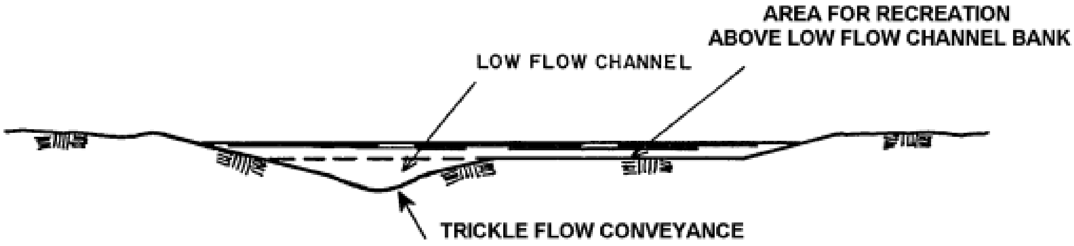
Figure OC-5: Typical Grassed Channels
(IDFCD USDCM 2002)



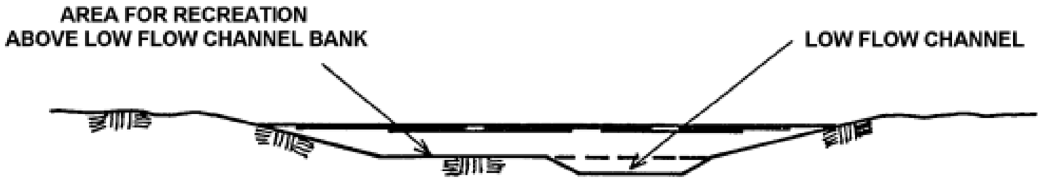
CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL



CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL



CROSS SECTION WITH LOW FLOW CHANNEL WITH TRICKLE CHANNEL
AREA FOR MAJOR DRAINAGE RUNOFF



CROSS SECTION WITH LOW FLOW CHANNEL WITH
OVERFLOW AREA FOR MAJOR DRAINAGE RUNOFF

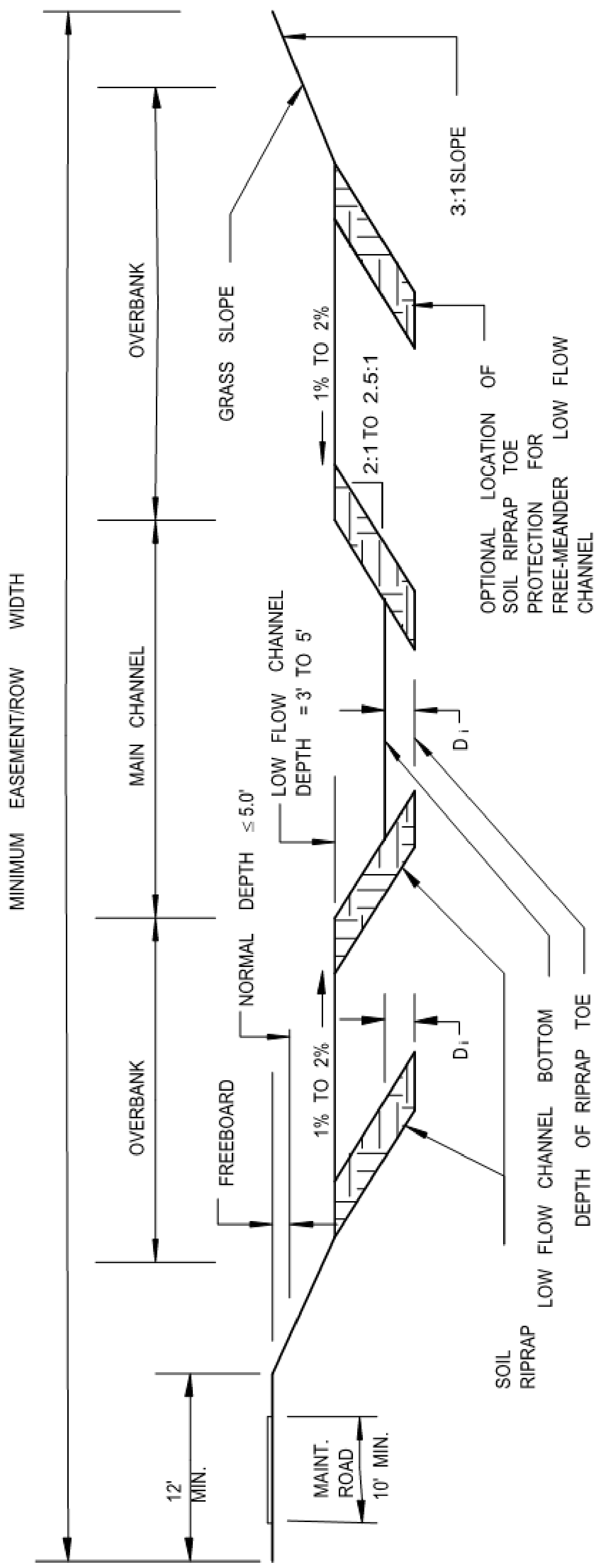
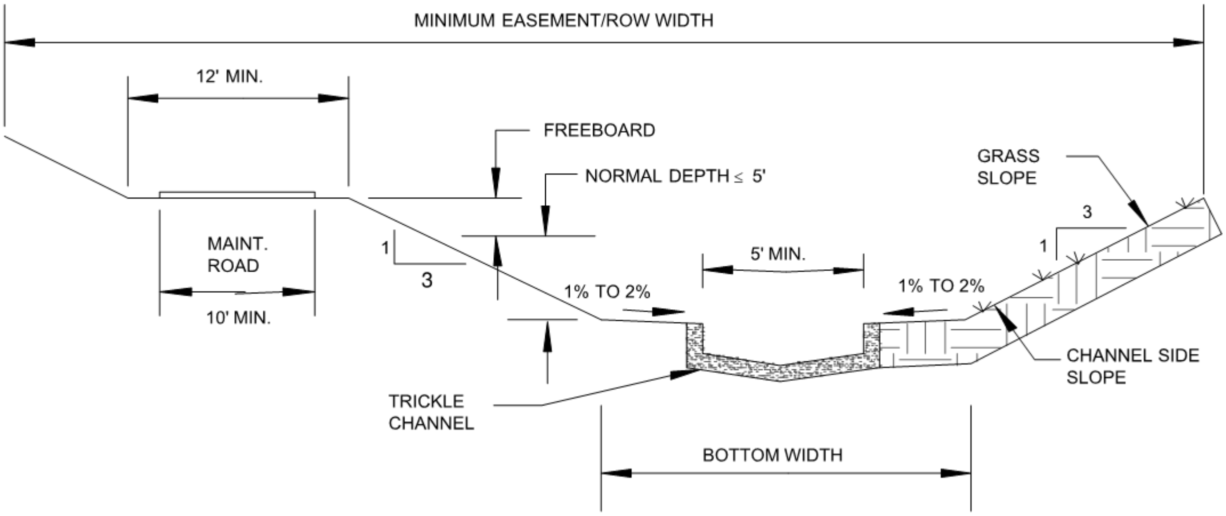


Figure OC-6: Composite Grass-lined Channel with a Low-Flow Channel, including a Wetland Bottom Low-Flow Channel
(UDFCD USDCM 2002)

Notes:

1. Low Flow Channel: Capacity to be able to pass the 5-year storm peak discharge based on fully developed tributary watershed peak flow.
2. Normal Depth: Flow depth for 100-year flow shall not exceed 5-feet, not including the low flow channel depth. 100-year flow velocity at normal depth shall not exceed 5-fps.
3. Freeboard: Freeboard to be 12 inches (min.) for Tertiary and Secondary Channels and 24 inches (min.) for Primary channels.
4. Maintenance Access Road: Minimum stable width to be 10-feet with a clear width of 12-feet.
5. Right-of-Way Width: Minimum width to include freeboard and maintenance access road.
6. Overbank: Flow in excess of main channel to be carried in this area. Area may be used for recreation purposes.
7. D_i = 36 inches (minimum)
8. Channel side slope above low-flow channel 3H:1V or flatter, even if lined with soil riprap.
9. Froude number for all flows shall not exceed 0.8.
10. The channel can be designed to have the low-flow section to have a wetland bottom.

Figure OC-7: Grass-lined Channel with a Trickle Channel
(UDFCD USDCM 2002)



NOTE:

1. Bottom Width: Consistent with maximum allowable depth and velocity requirements shall not be less than trickle channel width.
2. Trickle Channel: Capacity to be approximately 2.0% of 100-year flow for the fully developed, un-detained condition tributary watershed peak flow. Use natural lining when practical.
3. Normal Depth: Normal depth at 100-year flow shall not exceed 5-feet. Maximum 100-year flow velocity at normal depth shall not exceed 5-fps.
4. Freeboard: Freeboard to be 12 inches (min.) for Tertiary and Secondary Channels and 24 inches (min.) for Primary channels.
5. Maintenance Access Road: Minimum stable width to be 10-feet with clear width of 12-feet.
6. Easement/Right-of-Way Width: Minimum width to include freeboard and maintenance access road.
7. Channel Side Slope: Maximum side slope for grassed channels to be no steeper than 3:1.
8. Froude Number: Maximum value for minor and major floods shall not exceed 0.8.

3.1.5 Erosion Control

Grassed channels are erodible to some degree. Experience has shown that it is uneconomical to design a grassed channel that is completely protected from erosion during a major storm. It is far better to provide reasonably erosion-resistant design with the recognition that additional control measures and corrective steps will be needed after a major runoff event. The use of drops and checks (see HEC-14 2006) at regular intervals in a grassed channel is almost always needed to safeguard the channel from serious degradation and erosion by limiting velocities in the channel and dissipating excess energy at these structures. Take advantage of other infrastructure crossing the channel, such as a concrete-encased sewer crossing the channel that can be designed to also serve the function of a grade control structure or a drop structure. Erosion tends to occur at the edges and immediately upstream and downstream of a drop. Proper shaping of the crest and the use of riprap at all drops is necessary. Grade control structures will also protect healthy and mature native vegetation (i.e., trees, shrubs, grasses, wetlands) and reduce long-term maintenance needs.

3.1.5.1 Erosion at Bends

Special erosion control measures are often needed at bends, (see Section 3.1.1.4). An estimate of protection and velocity along the outside of the bend needs to be made using the following guidelines: When $r_c/T \geq 8.0$ (r_c = channel centerline radius, T = top width of water during the major design storm), no erosion protection is needed for the bank on the outside of the bend for channels meeting the velocity and depth criteria specified in this *Manual* for grass-lined channels. When $r_c/T < 8.0$, protect the bank on the outside of the bend with TRMs or riprap sized per Section 3.4.2.3 using an adjusted channel velocity determined using Equation OC-10.

$$V_a = (-0.147 * \frac{r_c}{T} + 2.176) * V$$ **(Equation OC-10)**

in which:

V_a = adjusted channel velocity for riprap sizing along the outside of channel bends (fps)

V = mean channel velocity for the peak flow of the major design flood (fps)

r_c = channel centerline radius (ft)

T = Top width of water during the major design flood (ft)

TRMs or riprap shall be applied to the outside 25% of the channel bottom and to the channel side slope for the entire length of the bend plus a distance of *T* upstream and 2 times *T* downstream of the bend. When using riprap, as an alternative to lining the channel bottom, extend the riprap liner at the channel side slope to 5-feet below the channel’s bottom.

3.1.5.2 Riprap Lining of Grass-lined Channels

For long-term maintenance needs, it is required that riprap channel linings be used only in the low-flow channel portion of a composite channel, but not on the banks above the low-flow channel section, nor on the banks of other grass-lined channels, with the exception of use of riprap at bends as discussed above. For this reason whenever soil-riprap linings are used above the low-flow section, a side-slope typically used for grass-line channels is required (i.e. 3H:1V).

3.1.6 Water Surface Profile

Water surface profiles shall be computed for all channels, for the 10-year and 100-year events. Computation of the water surface profile shall include standard backwater methods, taking into consideration all losses due to changes in velocity, drops, bridge openings, and other obstructions. Computations shall begin at a known point and extend in an upstream direction for subcritical flow. It is for this reason that the channel shall be designed from a downstream direction to an upstream direction. It is necessary to show the hydraulic and energy grade lines on all preliminary and final drawings to help ensure against errors.

The designer must remember that open-channel flow in urban settings is usually non-uniform because of bridge openings, curves, and structures. This necessitates the use of backwater computations for all final channel design work. Additional information on generating water surface profiles for channels containing bridges and other structures can be found in Chapter 8 – *Culvert / Bridge Hydraulic Design*. The designer is encouraged to make use of computer modeling software, such as HEC-RAS, to carry out water surface profile calculations and checks.

3.1.7 Maintenance

Grass-lined channels must be designed with maintainability in mind. Section 2.3.4 provides guidance for elements of design that permit good maintenance of these installations.

3.1.8 Calculation Tool

Calculations for sizing of a grass-lined channel using hydraulic equations from Section 2.0 and criteria from Section 3.1 can be used for the design of a grass-lined channel with a low-flow channel.

3.2 Composite Channels

When the trickle channel flow capacity limits (See Section 3.1.4) are exceeded, the use of a composite channel is required. Primarily a channel with a stabilized low-flow section and an overflow section above it to carry major flow. Composite channels are, in essence, grass-lined channels in which more dense vegetation (including wetland-type) is encouraged to grow on the bottom and sides of the low-flow channel. Hence they are sometimes known as “wetland bottom” channels. Under certain circumstances, such as when existing wetland areas are affected or natural channels are modified, the USACE’s Section 404 permitting process may mandate the use of composite channels that will have wetland vegetation in their bottoms. In other cases, a composite channel with a wetland bottom low-flow channel may better suit an individual site’s needs if used to mitigate wetland damages elsewhere or if used to enhance urban stormwater runoff quality. Composite channels can be closely related to bioengineered and natural channels. Composite channels can provide aesthetic benefits, habitat for aquatic, terrestrial and avian wildlife and water quality enhancement as base flows come in contact with vegetation.

Wetland bottom vegetation within a composite channel will trap sediment and, thereby, reduce the low-flow channel’s flood carrying capacity over time. To compensate for this, the channel roughness factor used for design must be higher than for a grass-lined channel. As a result, more right-of-way is required for composite channels that have the potential for developing wetlands in their bottom.

3.2.1 Design Criteria

The simplified design procedures in this *Manual* are based on assumptions that the flow depth is affected by the maturity of vegetation in the low-flow channel which affects the channel roughness and the rate of sediment deposition on the bottom. These assumptions are based on modern hydraulic publications and observed sediment loading of stormwater-laden streams in urban areas across the country.

The recommended criteria parallel the criteria for the design of grass-lined channels (Section 3.1), with several notable differences. Composite channels are, in essence, grass-lined channels in which more dense vegetation (including wetland-type) is encouraged to grow on the bottom and sides of the low-flow channel. From a design perspective, composite channels are differentiated from smaller grass-lined channels by (1) the absence of an impermeable trickle channel, (2) gentler longitudinal slopes and wider bottom widths that encourage shallow, slow flows, (3) greater presence of hydrophytic vegetation along the channel's bottom and lower banks, and (4) non-applicability of the 1% to 2% cross-slope criterion. (See figures in Section 3.1) Another major difference is that a wetland bottom channel should be designed as a low-flow channel having a capacity to carry the 2-year flood peak, instead of the 33% to 50% of the 2-year peak required for low flow channels. Figure OC-5 illustrates a representative wetland bottom composite channel.

The use of an appropriate Manning's n in the design of a composite channel is critical. In designing low-flow channels for composite channels, the engineer must account for two flow roughness conditions. To ensure vertical stability, the longitudinal slope of the channel should be first calculated and fixed assuming there is no wetland vegetation on the bottom (i.e. "new channel"). Next, in order to ensure adequate flow capacity after the low-flow channel vegetation matures and some sedimentation occurs, the channel's bottom is widened to find the channel cross section needed to carry the design flow using roughness coefficients under the "mature channel" condition. To allow for the "mature channel" condition and potential sediment accumulation, outfalls into channels with low-flow channels shall be at least 2 feet above the low-flow channel invert. The design procedure outlined below provides the reader with the necessary steps and specific channel criteria to carry out a design of a composite channel.

3.2.2 Design Procedure

If a composite channel is to be used, the following steps outline the specific design procedures necessary:

1. Design Discharge – Determine the 2-year peak flow rate in the wetland channel without reducing it for any upstream ponding or flood routing effects.
2. Channel Geometry – Define the newly-built channel's geometry to pass the design 2-year flow rate at less than 4 fps with a channel depth between 2- and 4-feet. The channel cross section should be trapezoidal with side slopes of 3:1 (H/V) or flatter. Bottom width shall be more than 5-feet.
3. Longitudinal Slope – Set the longitudinal slope using Manning's equation and a Manning's roughness coefficient of n=0.035, for the 2-year flow rate but no flatter that 0.0025 ft/ft. If the desired longitudinal slope cannot be satisfied with existing terrain, grade control checks or small drop structures must be incorporated to provide desired slope.
4. Low-flow Channel Capacity – Calculate the mature channel capacity during a 2-year flood using a Manning's roughness coefficient of n=0.065 and the same geometry and slope used when initially designing the channel with n=0.035.
5. Full-width Channel Capacity – After the low-flow channel has been designed to pass the 2-year storm peak discharge, complete the composite channel design by providing additional channel capacity through design/analysis of channel overbank areas. The final Manning's *n* for the composite channel shall be determined using Equation OC-11. Use Table OC-7 for Manning's *n* values for the middle area (low-flow), left overbank, and right overbank areas of a composite channel.

$$n_c = \frac{P * R^{5/3}}{\frac{P_L * R_L^{5/3}}{n_L} + \frac{P_M * R_M^{5/3}}{n_M} + \frac{P_R * R_R^{5/3}}{n_R}} \qquad \textbf{(Equation OC-11)}$$

In which:

n_C = Manning's *n* for the composite channel

n_L = Manning's *n* for the left overbank (…if grass-lined see Table OC-8)

n_R = Manning's *n* for the right overbank (…if grass-lined see Table OC-8)

n_M = Manning's *n* for the middle area (low-flow)

when, 2-ft ≤ y_0 < 5-ft, $n_M = 0.0018 * y_0^2 - 0.0206 * y_0 + 0.099$ **(Equation OC-11a)**

or 5-ft ≤ y_0 < 10-ft, $n_M = 0.0001 * y_0^2 - 0.0025 * y_0 + 0.050$ **(Equation OC-11b)**

where, y_0 = depth of flow

P_L = Wetted perimeter of the left overbank (ft)

P_R = Wetted perimeter of the right overbank (ft)

P_M = Wetted perimeter of the middle area (ft)

R_L = Hydraulic radius of the left overbank (ft)

R = Hydraulic radius of the right overbank (ft)

R_M = Hydraulic radius of the middle area (ft)

Table OC-9: Values for Manning's *n* in Grass-lined Overflow Bank Areas in Composite Channel (Guo 2006)

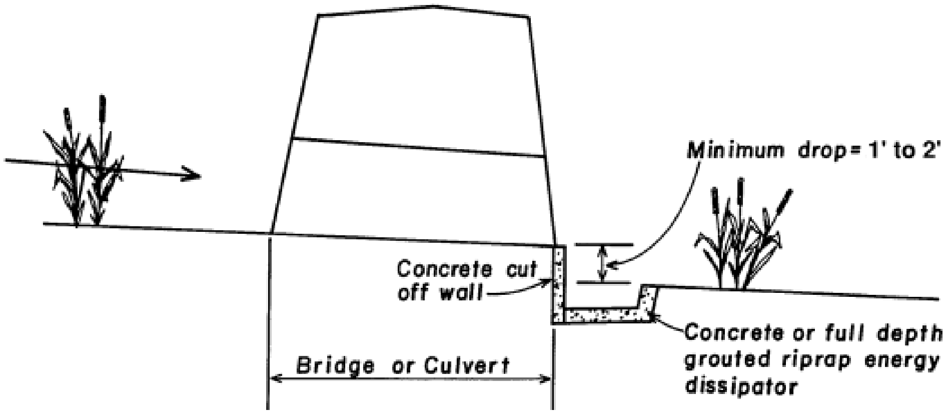
Grass Type	Grass Length	0.1 feet < Depth < 1.5 feet For Minor Runoff	Depth over 3.0 feet For Major Runoff
Bermuda	2-inch	0.0350	0.0300
	4-inch	0.0400	0.0300
Kentucky	2-inch	0.0350	0.0300
	4-inch	0.0400	0.0300
Grass (Good Stand)	12-inch	0.0700	0.0350
	24-inch	0.1000	0.0350
Grass (Fair Stand)	12-inch	0.0600	0.0350
	24-inch	0.0700	0.0350

6. Flooding Control Design Capacity – The channel shall also provide enough capacity to contain the flow during a 100-year flood while adhering to free-board requirements for the type of channel (primary, secondary, or tertiary) for which the channel design falls under. Adjustment of the channel capacity may be done by increasing the bottom width of the channel. Minimum bottom width shall be 5-feet.

3.2.3 Water Surface Profile

Whenever a composite bottom channel is crossed by a road, railroad, or a trail requiring a culvert or a bridge, a drop structure shall be provided immediately downstream of such a crossing. This will help reduce sediment deposition in the crossing. A 1-foot to 2-foot drop is required (a larger drop may be preferred in larger systems) on the downstream side of each culvert and crossing of a wetland bottom channel. See Figure OC-8 on the next page.

Figure OC-8: Composite Channel at Bridge or Culvert Crossing
(UDFCD USDCM 2002)



Water surface profiles must be computed, for the 10- and 100-year events. Computation of the water surface profile shall utilize standard backwater methods, taking into consideration all losses due to changes in velocity, drops, bridge openings, and other obstructions. Computations begin at a known point and extend in an upstream direction for subcritical flow. It is necessary to show the energy gradient on all preliminary and final drawings to help prevent errors.

The designer must remember that open-channel flow in urban drainage is usually non-uniform because of bridge openings, curves, and structures. This necessitates the use of backwater computations for all final channel design work.

3.2.4 Life Expectancy and Maintenance

The low-flow channel can serve as a productive ecosystem and can also be highly effective at trapping sediment. A composite channel with a wetland bottom is expected to fill with sediment over time. Some sediment accumulation is necessary for a “wetland bottom” channel’s success to provide organic matter and nutrients for growth of biological communities. The life expectancy of such a channel will depend primarily on the land use of the tributary watershed. However, life expectancy can be dramatically reduced to as little as 2 to 5 years if land erosion in the tributary watershed is not controlled. Therefore, land erosion control practices need to be strictly enforced during land development and other construction within the watershed, and all facilities shall be built to minimize soil erosion to maintain a reasonable economic life for the wetland bottom channel. In addition, sediment traps or forebays located at stormwater runoff points of entry can trap a significant portion of the sediment arising at the wetland channel and, if used, could decrease the frequency of major channel dredging.

3.2.5 Calculation Tool

Calculations for sizing of a composite channel can be performed using hydraulic equations from Section 2.0 and criteria from Section 3.2.

3.3 Concrete-Lined Channels

The use of concrete-lined channels requires City approval. Safety and aesthetic reasons; hydraulic; topographic; and/or right-of-way constraints may necessitate the use of a concrete-lined channel although they are not recommended for general use. A common constraint requiring a concrete-lined channel is the need to convey high velocity, sometimes supercritical, flow. Whether the flow will be supercritical or subcritical, the concrete lining must be designed to withstand the various forces and actions that cause overtopping of the bank, damage to the lining, and erosion of unlined areas.

Concrete-lined channels can be used for conveyance of both subcritical and supercritical flows. In general, however, other types of channels such as grass-lined channels or channels with wetland bottoms shall be used for subcritical flows. The use of a concrete-lined channel for subcritical flows shall not be used except in unusual circumstances where a narrow right-of-way exists.

3.3.1 Design Criteria

3.3.1.1 Design Velocity and Froude Number

Concrete channels can be designed to convey supercritical or subcritical flows. However, the designer must take care to prevent the possibility of unanticipated hydraulic jumps forming in the channel. For concrete channels, flows with *Froude Numbers* between 0.7 and 1.4 are unstable and unpredictable and shall be avoided at all flow levels in the channel. When a concrete channel is unavoidable, the maximum velocity at the peak design flow shall not exceed 18 feet per second.

To calculate velocities, the designer shall utilize Manning's Equation (Equation OC-2) from Section 2.1.1 of this chapter with roughness values from Table OC-9. When designing a concrete-lined channel for subcritical flow, use a Manning's n = 0.013 for capacity calculations and 0.011 to check whether the flow could go supercritical. Do not design a subcritical channel for a Froude number greater than 0.7 using the velocity and depth calculated with a Manning's n = 0.011. Also, do not design supercritical channel with a Froude Number less than 1.4 when checking for it using a Manning's n = 0.013.

Table OC-10: Manning's *n* Roughness Coefficients for Concrete-Lined Channels
(UDFCD USDCM 2002)

Type of Concrete Finish	Roughness Coefficient (*n*)		
	Minimum	**Typical**	**Maximum**
Concrete:			
Float finish*	0.013	0.015	0.016
Finished, with gravel on bottom*	0.015	0.017	0.020
On good excavated rock	0.017	0.020	0.023
On irregular excavated rock	0.022	0.027	0.030
Shotcrete, trowelled but not wavy	0.016	0.018	0.023
Shotcrete, trowelled and wavy	0.018	0.020	0.025
Shotcrete, unfinished	0.020	0.022	0.027
Trowel finish*	0.011	0.013	0.015
Unfinished*	0.014	0.017	0.020

* For a *subcritical* channel with these finishes, check the Froude number using $n = 0.011$

3.3.1.2 Design Depths

There are no specific limits set for depth for concrete-lined channels, except as required for low-flow channels of a composite section where the low-flow channel is concrete lined (see Section 3.1.4).

3.3.1.3 Curvature

Curvature is not allowed for channels with supercritical flow regimes. For concrete-lined channels with subcritical flow regimes, the thalweg radius of curvature shall be at least twice the top width, and super-elevation shall be evaluated for at each bend using Equation OC-9 in Section 2.2.4 and included in determining freeboard.

3.3.1.4 Design Discharge Freeboard

Freeboard above the design water surface shall not be less than that determined by the following:

$$H_{fb} = 2.0 + 0.025 * V * (y_0)^{1/3} + \Delta y \qquad \textbf{(Equation OC-12)}$$

in which:

H_{fb} = Freeboard height (ft)

V = Velocity of flow (ft/sec)

y_o = Depth of flow (ft)

Δy = Increase in water surface elevation due to super-elevation at bends (see Equation OC-9) (no bends allowed in supercritical channels)

In addition to H_{fb}, add height of estimated standing roll waves, super-elevation and/or other water surface disturbances to calculate the total freeboard. In all cases, the freeboard shall be no less than 12 to 24 inches and the concrete lining shall be extended above the flow depth to provide the required freeboard.

3.3.2 Concrete Lining Specifications

3.3.2.1 Concrete Lining Section

All concrete lining shall be designed to withstand the anticipated hydrodynamic and hydrostatic forces, and the minimum thickness shall be no less than 8-inches for supercritical channels and no less than 5 inches for subcritical channels. Free draining granular bedding shall be provided under the concrete liner. The bedding shall be no less than 6 inches thick for channels with Froude number less than 0.7; and 9 inches thick for channels with Froude number over 1.4. Concrete shall comply with Class M concrete according to AHTD's *Standard Specification for Highway Construction – Section 802 – Concrete for Structures.*

3.3.2.2 Concrete Joints and Reinforcement

Concrete joints must satisfy the following criteria:

1. Channels shall be constructed of continuously reinforced concrete. Channels constructed 8 inches thick shall be reinforced with #4 rebar at 12 inch transverse spacing and #4 rebar at 18 inch longitudinal spacing. Channels constructed 6 inches thick shall be reinforced with 6x6–8/8 welded wire mesh. All reinforcement shall be installed so it is 2 inches from the bottom of the concrete slab.
2. Expansion/contraction joints shall be installed where new concrete lining is connected to a rigid structure or to existing concrete lining which is not continuously reinforced. Expansion joints shall be constructed at a minimum distance of 50-feet between joints and in no case shall exceed 75-feet. Expansion joint fillers shall be of a non-extruding type conforming to ASTM designation D1751.
3. Saw joints are to be made at 10-foot spacing maximum on all ditch sections. All saw joints shall have backer rod and caulking properly installed per manufacture's specifications. Materials used to seal saw joints shall be on AHTD's Qualified Products List.
4. Longitudinal joints, where required, shall be constructed on the sidewalls at least 1-foot vertically above the channel invert.
5. All joints shall be designed to prevent differential movement.

6. Construction joints are required for all cold joints and where the lining thickness changes. Reinforcement shall be continuous through the joint.

Fiber reinforcement in the concrete mix (as a replacement for steel reinforcement) will be allowed once the City has reviewed the material specifications. City inspection personnel must also be present for several of the first batches to confirm that the fiber being added is what was approved and to determine if construction personnel adequately finish the concrete to meet all other requirements. All other joint requirements above must be met.

3.3.2.3 Concrete Finish

The surface of the concrete lining may be finished in any of the finishes listed in Table OC-11, provided an appropriate finishing technique is used.

3.3.2.4 Weep Holes

Weep holes shall be required in all impervious lined channels. Weep holes at a minimum shall be 2 inches in diameter and placed every 10 fee on center along the channel sides. Crushed rock (1/2-inch to 5/8-inch) wrapped in 6-ounce non-woven filter fabric shall be placed in front of the weep holes to prevent loss of the channel subgrade. See Figure OC-9 .

3.3.3 Channel Cross Section

3.3.3.1 Side Slopes

The side slopes shall be no steeper than 1.5V:1H unless designed to act as a structurally reinforced wall to withstand soil and groundwater forces. In some cases, a rectangular cross section may be required. Rectangular cross sections are acceptable provided they are designed to withstand potential lateral loads and adhere to the safety requirements outlined in Section 3.3.4.

3.3.3.2 Depth

Maximum depth shall be consistent with Section 3.3.1.2. For known channel geometry and discharge, normal water depth can be calculated using Manning's Equation (Equation OC-2) from Section 2.1.1.

3.3.3.3 Bottom Width

The bottom width shall be designed to satisfy the hydraulic capacity of the cross section recognizing the limitations on velocity, depth, and Froude number. For a given discharge, the bottom width can be calculated from depth, velocity, slope, and Froude number constraints in Section 3.3.1.1, Section 3.3.1.2, and Section 3.3.1.3 using Manning's Equation. In no case shall the bottom of the channel be any less than 5-feet wide.

3.3.3.4 Trickle and Low-Flow Channels

For a well-designed concrete-lined channel, a trickle or low-flow channel is not necessary since the entire channel is hard-lined. However, if a small base flow is anticipated, it is a good idea to incorporate a trickle flow swale or section to reduce occurrence of bottom slime, noxious odors and mosquito breeding. The trickle flow swale shall be integral to the concrete-lined channel bottom.

3.3.3.5 Outfalls into Channel

Outfalls into concrete-lined channels shall be at least 12 inches above the channel invert.

3.3.4 Safety Requirements

A 6-foot tall chain-link or comparable fence, handrail, or other safety barrier shall be installed to prevent access whenever the 100-year channel concrete section depth exceeds 3 feet. An appropriate numbers of gates with top latches shall be placed and staggered where a fence is required on both sides of the channel to permit good maintenance access.

In addition, ladder-type steps shall be installed not more than 200 feet apart on alternating sides of the channel. A bottom rung shall be placed approximately 12 inches vertically above the channel invert.

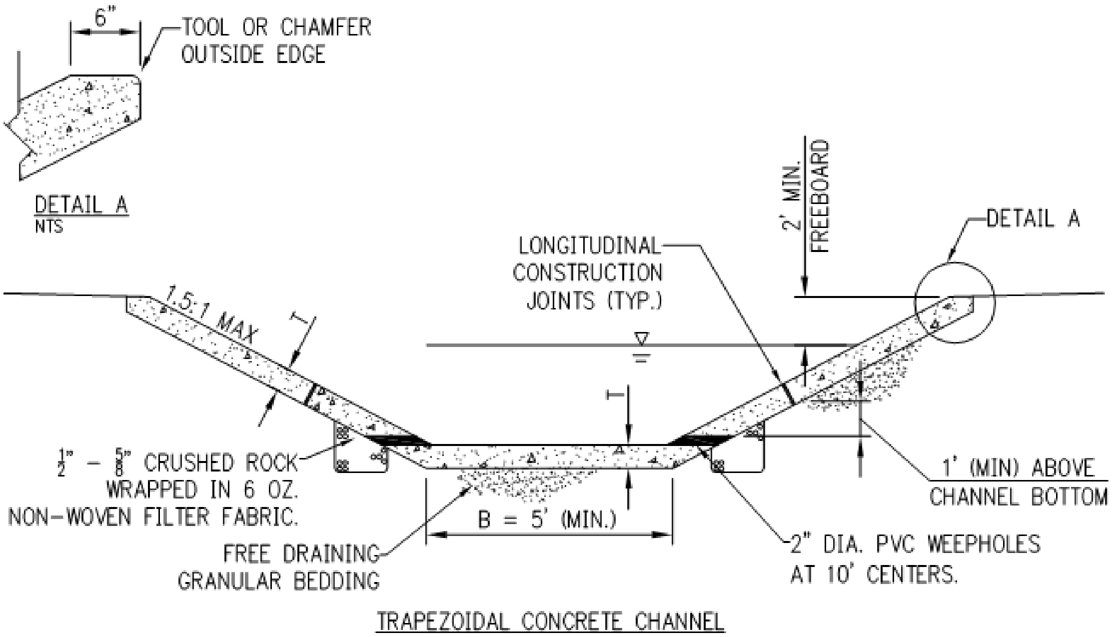
3.3.5 Calculation Tools

Calculations for sizing of a concrete-lined channel can be performed using hydraulic equations from Section 2.0 and criteria from Section 3.3.

3.3.6 Maintenance

Concrete channels require periodic maintenance including debris and sediment removal, patching, joint repair, and other such activities. Their condition should be periodically monitored, especially to assure that flows cannot infiltrate beneath the concrete lining.

Figure OC-9: Concrete Lined Channel (Trapezoidal)



Notes:

1. Fr ≤ 0.7, T = 5” reinforcement with 6X6-8/8 WWM installed 2” from the bottom of the slab; and provide 6 inch minimum free draining granular bedding under the concrete section.
   Fr ≥ 14, T = 8” reinforcement with #4 rebar at 12” transverse installed 2” from the bottom of the slab; and #4 rebar at 18” longitudinal. Provide minimum of 9” free draining granular bedding under the concrete section.
2. Concrete work shall conform to the requirements of the City technical specifications.
3. Install expansion joints at 50 foot minimum spacing not to exceed 75 feet maximum. Saw joints at 10-foot spacing maximum on all ditch sections. All saw joints are to have backer rod and caulking properly installed per manufacturer’s specifications.

3.4 Riprap-Lined Channels

The use of riprap-lined channels is discouraged and requires City approval. Channel linings constructed from riprap (grouted or partially grouted), soil riprap, grouted boulders, or wire-encased rock (gabion) to control channel erosion may be considered on a case-by-case basis or as required for the following situations:

1. Where major flows such as the 100-year flood are found to produce channel velocities in excess of allowable non-eroding values (4-ft/sec) or when main channel depth is greater than 5 feet.
2. Where channel side slopes must be steeper than 3H:1V.
3. For low-flow channels.
4. Where rapid changes in channel geometry occur such as channel bends and transitions.

Design criteria applicable to these situations are presented in this section. Riprap-lined channels shall only be used for subcritical flow conditions where the Froude number is 0.8 or less. Loose stones serving as a protective blanket will not be accepted for riprap lining. Instead riprap shall either receive a full grout matrix or be partially grouted. The type of grouting (full or partial) a riprap lining is to receive will be determined by the City. The grout for a full grout matrix shall adhere to the methods and specifications outlined in Table OC-13 of this *Manual*. Furthermore, requirements for grouted riprap shall adhere to AHTD's *Standard Specification for Highway Construction – Section 816 – Filter Blanket and Riprap* for *Dumped Riprap (Grouted)*. Partially grouted riprap shall be designed, specified, and constructed according to the criteria presented in FHWA's HEC 23 (2001) and other trusted sources on the subject. Furthermore, when used, it is required that all riprap outside frequent flow zones have the voids filled with soil so that the top of the rock is covered and the surface is re-vegetated with native grasses. This combination of riprap, soil, and vegetation is considered *soil riprap*.

3.4.1 Types of Riprap

3.4.1.1 Riprap and Soil Riprap

Many factors govern the size of the rock necessary to resist the forces tending to move the riprap. For the riprap itself, this includes the size and weight of the individual rocks; shape of the stones; gradation of the particles; blanket thickness; type of bedding under the riprap; and the slope of the riprap layer. Hydraulic factors affecting riprap include the velocity; current direction; eddy action; waves; and hydraulic uplift forces.

Experience has shown that riprap failures result from a variety of factors: undersized individual rocks in the maximum size range; improper gradation of the rock, which reduces the interlocking of individual particles; and improper bedding of the riprap, which allows leaching of channel particles through the riprap blanket.

Classification and gradation for riprap and boulders are given in Table OC-11 and Table OC-12 and are based on a minimum specific gravity of 2.50 for the rock. Because of its relatively small size and weight, riprap Types 1 and 2 must be used in soil riprap applications only. Type 3 riprap shall be used for all other riprap lining needs. This practice also protects the rock from vandalism.

Soil Riprap consists of 35% by volume of native soil that is taken from the banks of the channel and mixed with 65% by volume of riprap on-site just before placement as a channel liner. Soil riprap is required for all urban channels within the City regardless of riprap size used. A typical section for soil riprap installation is illustrated in Figure OC-12 on the next page.

Table OC-11: Classification and Gradation of Riprap

Riprap Designation	d_{50}*	Maximum Rock Size	…a gradation where less than 15% will be less than ___ in size
Type 1	6** inches	10 inches	3 inches
Type 2	12** inches	20 inches	4 inches
Type 3	18 inches	28 inches	6 inches

* d_{50} = mean particle size (intermediate dimension) by weight.

** When used as soil riprap, mix Type 1 and Type 2 riprap with 35% topsoil (by volume); bury it with 4 inches of topsoil; all vibration compacted; and re-vegetated.

Note: Bedding material must be used under riprap. Bedding material shall consist of granular bedding as shown in Table OC-15.

Basic requirements for riprap stone are as follows:

- Rock shall be hard, durable, angular in shape, and free from cracks, overburden, shale, and organic matter.
- Neither breadth nor thickness of a single stone shall be less than one-third its length, and rounded stone shall not be used.
- The rock shall be from a source with a percent of wear not greater than 45% calculated by the Los Angeles Abrasion Test (AASHTO T 96) and shall sustain a loss of not more than 10% after 12 cycles of freezing and thawing (AASHTO test 103 for ledge rock procedure A).
- Rock having a minimum specific gravity of 2.65 is preferred. However, in no case shall rock have a specific gravity less than 2.50.
-

3.4.1.2 Grouted Boulders

Table OC-12 provides the classification and size requirements for boulders. When grouted boulders are used, they provide a relatively impervious channel lining which is less subject to vandalism than riprap. Grouted boulders require less routine maintenance by reducing silt and trash accumulation and are particularly useful for lining low-flow channels and steep banks. The appearance of grouted boulders is enhanced by exposing the tops of individual stones and by cleaning the projecting rocks with a wet broom right after the grouting operation. In addition, it is required that grouted boulders on channel banks and outside of frequent flow areas be buried with topsoil and re-vegetated with native grasses, with or without shrubs depending on the local setting. Boulders used for grouting shall meet all the properties of rock for riprap, and rock of uniform size shall be used. The boulder sizes are categorized in Table OC-12.

Table OC-12: Classification of Boulders (UDFCD USDCM 2002)

Boulder Classification	Nominal Size and [Range in Smallest Dimension of Individual Rock Boulders]	Maximum Ratio of Largest to Smallest Rock Dimension of Individual Boulders
Type B18	18 [17 – 20] inches	2.5
Type B24	24 [22 – 26] inches	2.0
Type B30	30 [28 – 32] inches	2.0
Type B36	36 [34 – 38] inches	1.75
Type B42	42 [40 – 44] inches	1.65
Type B48	48 [45 – 51] inches	1.50

Grouted boulders shall be placed directly on subbase without granular bedding. The top 50% of the boulders shall be left ungrouted and exposed. Weep holes shall be provided at the toe of channel slopes and channel drops to reduce uplift forces on the grouted channel lining. Underdrains shall be provided if water is expected to be present beneath the liner. Grouted boulders on the banks shall be buried and vegetated with dry-land grasses and shrubs. Cover the grouted boulders with slightly compacted topsoil by filling depressions and covering the top of the tallest rocks to a height of no less than 6-inches to establish dry-land vegetation. Staked sod shall be placed to the 100-year storm depth. Shrubs also may be planted, but will not grow well over grouted boulders unless irrigated.

Two types of grout, Type A and Type B, are allowed for filling the voids of grouted boulders. The technical specifications for two types of structural grout mix are given in Table OC-13. Type A can be injected using a low-pressure grout pump and can be used for the majority of applications. Type B has been designed for use in streams and rivers with significant perennial flows where scouring of Type A grout is a concern. It requires a concrete pump for injection.

Full penetration of grout around the lower 50% of the rock is essential for successful grouted boulder performance. Inject grout in a manner that ensures that no air voids between the grout, subbase, and boulders will exist. To accomplish this, inject the grout by lowering the grouting nozzle to the bottom of the boulder layer and build up the grout from the bottom up, while using a vibrator or aggressive manual rodding. Inject the grout to a depth equal to 50% of the boulder size being used and keep the upper 50% ungrouted and clean. Remove all grout splatters from the exposed boulder portion immediately after grout injection using wet brooms and brushes.

Table OC-13: Specifications and Placement Instructions for Grout in Grouted Riprap and Grouted Boulders (UDFCD USDCM 2002)

Material Specifications	Placement Specifications
1. All grout shall have a minimum 28-day compressive strength equal to 3200 psi. 2. One cubic yard of grout shall have a minimum of 6 sacks of Type II Portland cement. 3. A maximum of 25% Type F Fly Ash may be substituted for the Portland cement. 4. For Type A grout, the aggregate shall be comprised of 70% natural sand (fines) and 30% 3/8-inch rock (coarse). 5. For Type B grout, the aggregate shall be comprised of 3/4-inch maximum gravel, structural concrete aggregate. 6. Type B grout shall be used in streams with significant perennial flows. 7. The grout slump shall be between 4 and 6 inches. 8. Air entrainment shall be between 5.5% and 7.5%. 9. To control shrinkage and cracking, 1.5 pounds of fiber reinforcement shall be used per cubic yard of grout. 10. Color additive in required amounts shall be used when specified by contract.	1. All Type A grout shall be delivered by means of a low pressure (less than 10 psi) grout pump using a 2-inch diameter nozzle. 2. All Type B grout shall be delivered by means of a low pressure (less than 10 psi) concrete pump using a 3-inch diameter nozzle. 3. Full depth penetration of the grout into the riprap/boulder voids shall be achieved by injecting grout starting with the nozzle near the bottom and raising it as grout fills, while vibrating grout into place using a pencil vibrator. 4. After grout placement, exposed riprap/ boulder faces shall be cleaned with a wet broom. 5. All grout between riprap/boulders shall be treated with a broom finish. 6. All finished grout surfaces shall be sprayed with a clear liquid membrane curing compound as specified in ASTM C-309. 7. Special procedures shall be required for grout placement when the air temperatures are less than 40°F or greater than 90°F. Contractor shall obtain prior approval from the design engineer of the procedures to be used for protecting the grout. 8. Clean riprap/boulders by brushing and washing before grouting.

3.4.1.3 Wire-Enclosed Rock (Gabions)

Wire-enclosed rock, or gabions, refers to rocks that are bound together in a wire basket so that they act as a single unit. The durability of wire-enclosed rock is generally limited by the life of the galvanized binding wire that has been found to vary considerably under conditions along waterways. Water carrying sand, gravel, or fine soil particles will reduce the service life of the wire dramatically. Water that rolls or otherwise moves cobbles and large stones will break the wire with a hammer-and-anvil action, considerably shortening the life of the wire. The wire has been found to be susceptible to corrosion by various chemical agents and is particularly affected by high-sulfate soils. If the designer chooses to utilize gabions, they shall be placed above the low-flow channel or 5-year water surface elevation. All flat mattresses must be filled with topsoil; covered with a 6-inch layer of topsoil; and then sodded, seeded, hydro-seeded, or planted with other approved vegetation. All material and construction requirements of gabions shall follow AHTD's *Standard Specification for Highway Construction – Section 629 – Gabions*, except for as amended in this *Manual*.

3.4.1.4 Alternatives to Riprap Lining/Structures

As discussed above, riprap lined channels are discouraged by the City and approval will be at staff discretion. As such, the City is open to alternative types of channel reinforcement to prevent scour and protect the channel bank and its invert. It is the responsibility of the design engineer to show their proposed method for preventing scour is as good if not superior to riprap. Any proposed alternative needs to show this by outlining its cost effectiveness, maintenance characteristics, engineering capabilities and applications, and long term potential. Alternatives to riprap that the City finds acceptable are turf reinforcement mats (TRMs); erosion control blankets (ECBs); hard-flexible armoring systems/units (i.e. CONTECH Hard Armor – Armortec); and gabions (as mentioned in Section 3.4.1.3) among many other systems and devices.

3.4.2 Design Criteria

The following sections present design criteria for riprap-lined channels. Additional information on riprap at storm sewer pipe outlets can be found in Chapter 5 – *Storm Sewer System Design*.

3.4.2.1 Design Velocity

Riprap-lined channels shall only be used for subcritical flow conditions where the Froude number is 0.8 or less.

3.4.2.2 Design Depths

There is no maximum depth criterion for riprap-lined channels. Wire-enclosed rock sections shall be used on banks only above the low-flow channel or 5-year flood water surface and must be placed on a stable foundation.

3.4.2.3 Riprap Sizing

The stone sizing for riprap can be related to the channel’s longitudinal slope, flow velocity, and the specific gravity of the stone using the relationship:

$$\frac{V * S^{0.17}}{d_{50}^{0.5} * (G_S - 1)^{0.66}} = 4.5$$ **(Equation OC-13)**

in which:

V = Mean channel velocity (ft/sec)

S = Longitudinal channel slope (ft/ft)

d_{50} = Mean rock size (ft)

G_s = Specific gravity of stone (minimum = 2.50)

Note that Equation OC-13 is applicable for sizing riprap for channel lining. This equation is not intended for use in sizing riprap for rundowns or culvert outlet protection. Information on protection downstream of culverts is discussed in Chapter 5 – *Storm Sewer System Design*.

Table OC-14 shall be used to determine the minimum size of rock type required. Note that rock types for riprap, including gradation, are presented in Table OC-11.

Table OC-14: Riprap Requirements for Channel Linings *
(UDFCD USDCM 2002 [modified for City of Bella Vista])

$\frac{V * S^{0.17}}{(G_S - 1)^{0.66}}$ **	Rock Type
Less than 3.3	Type 1** (d_{50} = 6 inches)
Between 3.3 and 4.6	Type 2 (d_{50} = 12 inches)
Over 4.6 to 5.6	Type 3 (d_{50} = 18 inches)

* Applicable only for a Froude less than 0.8 and side slopes no steeper than 2.5H:1V.

** Use G_s = 2.5 unless the source of rock and its density are known at time of design.

Table OC-14 provides riprap requirements for all channel side slopes up to and including 2.5H:1V. Rock-lined side slopes steeper than 2.5H:1V are unacceptable under any circumstances because of stability, safety, and maintenance considerations. Proper bedding is required both along the side slopes and the channel bottom for a stable lining. The riprap blanket thickness shall be at a minimum two-times (2x) d_{50} and shall extend up the side slopes at least 1-foot above the design water surface. At the upstream and downstream termination of a riprap lining, the thickness shall be increased 50% for at least 3-feet to prevent undercutting.

Where the required riprap size from Equation OC-13 exceeds those as defined in Table OC-11 the design engineer shall look at adjusting the channels geometry and/or slope in order to satisfy the requirements of Equation OC-13, review alternate channel linings, etc.

3.4.2.4 Riprap Toes

Where only the channel sides are to be lined and the channel bottom remains unlined, additional riprap extending below the channel bottom is needed to protect undermining the channel side lining. In this case, the riprap blanket shall extend at least 5-feet below the channel thalweg (invert/flowline), and the thickness of the side slope blanket below the existing channel bed shall be increased to at a minimum three-times (3x) d_{50} to accommodate possible channel scour during higher flows. The designer shall compute the scour depth for the 100-year flow and, if this scour depth exceeds 5-feet, the depth of the riprap blanket shall be increased accordingly.

3.4.2.5 Curves and Bends

The potential for erosion increases along the outside bank of a channel bend due to acceleration of flow velocities on the outside part of the bend. Thus, it is often necessary to provide erosion protection in channels that otherwise would not need protection. TRMs, riprap, and other structural controls provide the needed protection in these areas. The need for protection of the bank on the outside of the bend has been discussed in Section 3.1.5 for channel bends that have a radius less than 8 times the top width of the channel cross section.

The minimum allowable radius for a riprap-lined bend is twice the top width of the design flow water surface. The riprap protection shall be placed along the outside of the bank and shall be extended upstream from the bend a distance of not less than the top width of the channel. The protection shall also extend downstream from the bend a distance of not less than twice the top width of the channel. Whenever an outside bend in a grass-lined channel needs protection, soil riprap, TRMs, or other approved alternative shall be used, then covered with native topsoil and re-vegetated to provide a grassed-line channel appearance.

Where the mean channel velocity exceeds the allowable non-eroding velocity so that riprap protection is required for straight channel sections, increase the rock size using the adjusted flow velocity found using Equation OC-10. Use the adjusted velocity in Table OC-14 to select appropriate riprap size.

3.4.2.6 Transitions

Scour potential is amplified by turbulent eddies near rapid changes in channel geometry such as transitions and at structures (culverts, bridges, etc.). Table OC-14 may be used for selecting riprap protection for subcritical transitions (Froude numbers 0.8 or less) by using the maximum velocity in the transition and then increasing the velocity by 25%.

Protection must extend upstream from the transition entrance at least 5 feet and downstream from the transition exit for a distance equal to at least 5 times the design flow depth.

3.4.2.7 Design Discharge Freeboard

Freeboard above the design water surface shall not be less than that determined by Equation OC-12 in Section 3.3.1.4.

In addition to the freeboard height calculated using Equation OC-12, add the height of estimated standing waves and/or other water surface disturbances and calculate total freeboard. In all cases, the riprap lining shall be extended above the flow depth to provide freeboard.

3.4.3 Roughness Coefficient

The Manning's roughness coefficient, n, for a riprap-lined channel may be estimated for riprap using:

$$n = 0.0395 * d_{50}^{\ 1/6} \qquad \textbf{(Equation OC-14)}$$

In which, d_{50} = the mean stone size (ft)

This equation does not apply to grouted boulders or to very shallow flow (where hydraulic radius is less than, or equal to two-times (2x) the maximum rock size). In those cases the roughness coefficient will be greater than indicated by Equation OC-14 and shall be adjusted accordingly.

3.4.4 Bedding Requirements

The long-term stability of riprap erosion protection is strongly influenced by proper bedding conditions. A large percentage of all riprap failures is directly attributable to bedding failures.

Properly designed bedding provides a buffer of intermediate-sized material between the channel bed and the riprap to prevent channel particles from leaching through the voids in the riprap. Two types of bedding are commonly used: (1) a granular bedding filter and (2) filter fabric.

3.4.4.1 Granular Bedding

The acceptable method for establishing gradation requirements for granular bedding for riprap consists of either single or two-layer bedding that uses what is defined as Type I and Type II gradations, is shown in Table OC-15 on the next page.

Table OC-15: Gradation for Granular Bedding

U.S. Standard Sieve Size	Percent Weight by Passing Square-Mesh Sieves	
	Type I AHTD Sect. 501.02 Materials (b) Fine Aggregate	**Type II** AHTD Sect. 303 Aggregate Base Course, Class 4
3 inches	-----	90% to 100%
1½ inches	-----	-----
¾ inches	-----	60% to 90%
3/8 inches	100%	40% to 80%
#4	95% to 100%	30% to 60%
#8	70% to 95%	-----
#10	-----	20% to 45%
#16	45% to 85%	-----
#30	20% to 65%	-----
#40	-----	10% to 35%
#50	5% to 30%	-----
#100	0% to 5%	-----
#200	-----	3% to 12%

The Type I and Type II bedding specifications conform closely with AHTD's aggregate specifications. The Type I bedding in Table OC-15 is designed to be the lower layer in a two-layer filter for protecting fine-grained soils and has a gradation identical to AHTD's concrete fine aggregate specification AASHTO T27 (AHTD Section 501.02 (b)). Type II bedding, the upper layer in the two-layer filter, is equivalent to AHTD's Class 4 aggregate base course specification AASHTO T11 and T27 (AHTD Section 303), except that it permits a slightly larger maximum rock fraction above the 3/4-inch sieve. When the channel is created in coarse sand and gravel (50% or more of coarse sand and gravel retained on the #40 sieve by weight), only the Type II filter is required. Otherwise, a two-layer bedding (Type I topped by Type II) is required. Alternatively, a single 12-inch layer of Type II bedding can be used, except at drop structures. For required bedding thickness, see Table OC-16 below.

Table OC-16: Granular Bedding Thickness Requirements
(UDFCD USDCM 2002)

Riprap Designation	Minimum Bedding Thickness		
	Fine-Grained Soils*		Coarse-Grained Soils**
	Type I	Type II	Type II
Type 1 (d_{50} = 6 in)	4 inches	4 inches	6 inches
Type 2 (d_{50} = 12 in)	4 inches	4 inches	6 inches
Type 3 (d_{50} = 18 in)	4 inches	6 inches	8 inches

* May substitute one 12-inch layer of Type II bedding. The substitution shall not be permitted at drop structures. The use of a combination of filter fabric and Type II bedding at drop structures is acceptable.

** Fifty percent or more by weight retained on the # 40 sieve.

3.4.4.2 Filter Fabric

Filter fabric is not a substitute for granular bedding. Filter fabric provides filtering action only perpendicular to the fabric and has only a single equivalent pore opening between the channel bed and the riprap. Filter fabric has a relatively smooth surface, which provides less resistance to stone movement. As a result, it is recommended that the use of filter fabric be restricted to slopes no steeper than 3H:1V. Tears in the fabric greatly reduce its effectiveness; therefore, direct dumping of riprap on the filter fabric is not allowed and due care must be exercised during construction. Nonetheless, filter fabric has proven to be a workable supplement to granular bedding in many instances provided it is properly selected; installed; and not damaged during installation.

At drop structures and sloped channel drops, where seepage forces may run parallel to the fabric and cause piping along the bottom surface of the fabric, special care is required in the use of filter fabric. Seepage parallel with the fabric must be reduced by folding the edge of the fabric vertically downward about 2 feet (similar to a cutoff wall) at 12-foot intervals along the installation, particularly at the entrance and exit of the channel reach. Filter fabric has to be lapped a minimum of 12 inches at roll edges with the upstream fabric being placed on top of downstream fabric at the lap.

Fine silt and clay has been found to clog the openings in filter fabric. These materials prevent free drainage and increase the failure potential due to uplift. For this reason, a double granular filter is often more appropriate bedding for fine silt and clay channel beds. See Figure OC-11 for details on acceptable use of filter fabric as bedding.

3.4.5 Channel Cross Section

3.4.5.1 Side Slopes

For long-term maintenance needs, it is required that riprap channel linings be used only as toe protection in natural channel and in low-flow channel portion of an engineered channel, but not on the banks above the low-flow channel section. For this reason whenever soil-riprap linings are used above the low-flow section or above what is needed for toe protection, a slope typically used for grass-lined channels is required (i.e., 3H:1V).

Riprap-lined and soil riprap-lined side slopes steeper than 2.5H:1V are considered unacceptable because of stability, safety, and maintenance considerations. In some cases, such as under bridges and in retrofit situations where right-of-way is very limited, use of 2H:1V is subject to City approval. Any riprap-lined slope steeper than 2.5H:1V shall be subject to City approval.

3.4.5.2 Depth

The maximum depth shall be consistent with the guidelines in Section 3.4.2.2 of this chapter. For known channel geometry and discharge, normal water depth can be calculated using Manning's Equation from Section 2.1.1 of this chapter.

3.4.5.3 Bottom Width

The bottom width must be designed to satisfy the hydraulic capacity of the cross section, recognizing the limitations on velocity, depth, and Froude number. For a given discharge, the bottom width can be calculated from depth, velocity, slope, and Froude number constraints in Section 3.4.2.1, Section 3.4.2.2, and Section 3.4.2.3 using Manning's Equation from Section 2.1.1 of this chapter.

3.4.5.4 Outfalls into Channel

Outfalls into riprap-lined channels shall be at least 12 inches, but preferably 24 inches, above the channel invert.

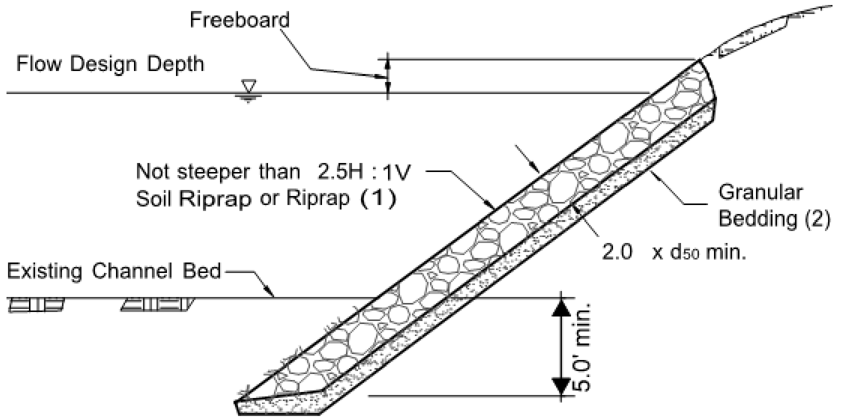
3.4.6 Erosion Control

For a properly bedded and lined riprap channel section, in-channel erosion should not generally be a problem. As with concrete channels, the primary concern is control of erosion in the watershed tributary leading up to the channel. Good erosion control practices in the watershed will reduce channel maintenance. In addition, accumulation of debris in the channel may be of concern due to the potential for movement of riprap and damming, especially after a large event.

3.4.7 Maintenance

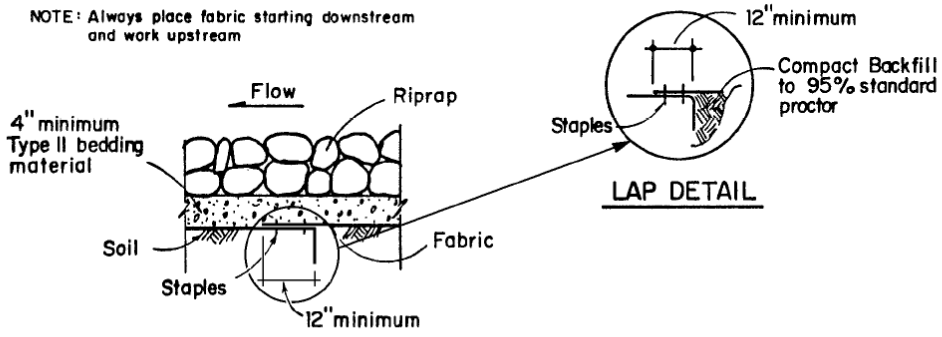
The greatest maintenance concern is the long-term loss of riprap. Also, grout used in grouting riprap can deteriorate with time so should be monitored as well. Improper grout installation creates long-term maintenance problems.

Figure OC-10: Riprap Channel Bank Lining, Including Toe Protection (UDFCD USDCM 2002)

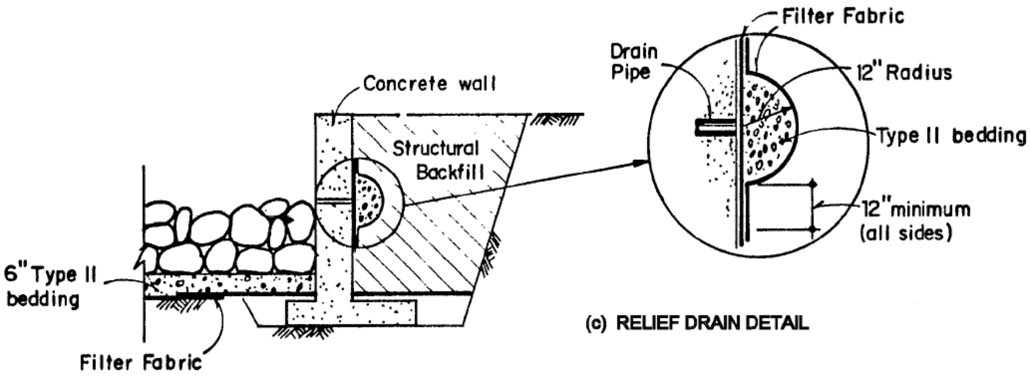


1. Use Soi Riprap when d_{50} is less than or equal to Type 1. Suggest use of Soil Riprap for larger riprap sizes as well.
2. Eliminate granular bedding when soil Riprap is used.

Figure OC-11: Filter Fabric Details (UDFCD USDCM 2002)

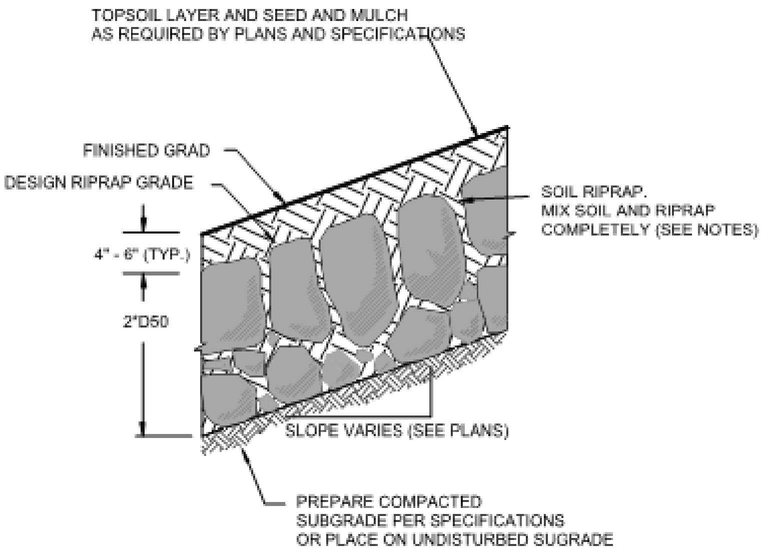


(a) TYPICAL LAP DETAIL AND FILTER FABRIC PLACEMENT

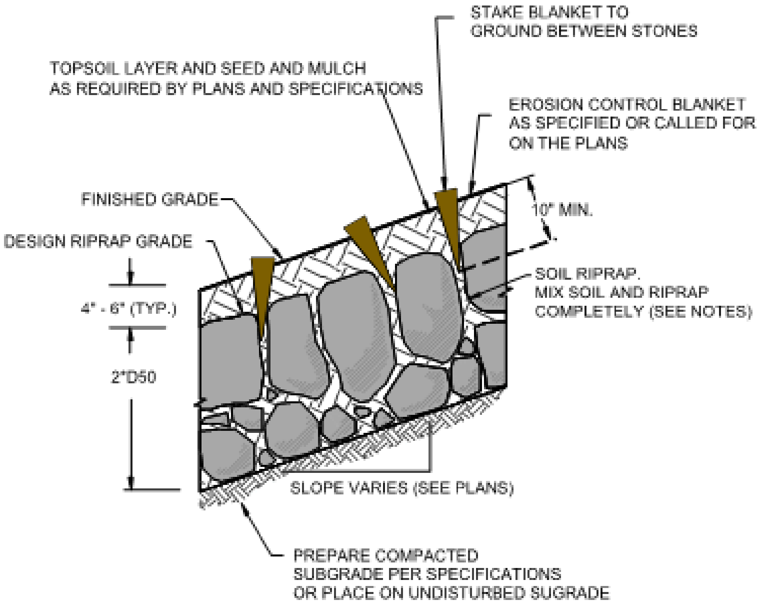


(c) RELIEF DRAIN DETAIL

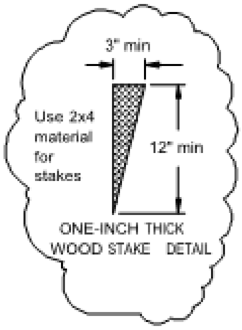
Figure OC-12: Soil Riprap Typical Details (UDFCD USDCM 2002)



Typical Section of Soil Riprap with Mulch



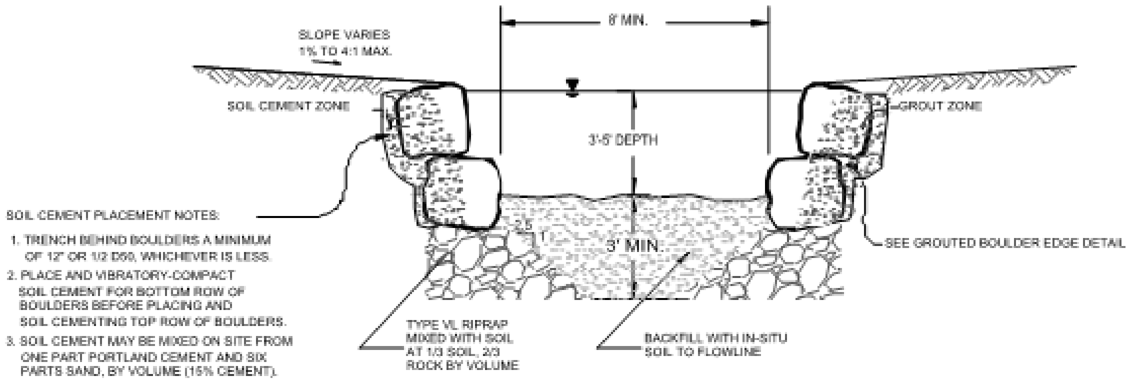
Typical Section of Soil Riprap with Erosion Control Blanket or Mat



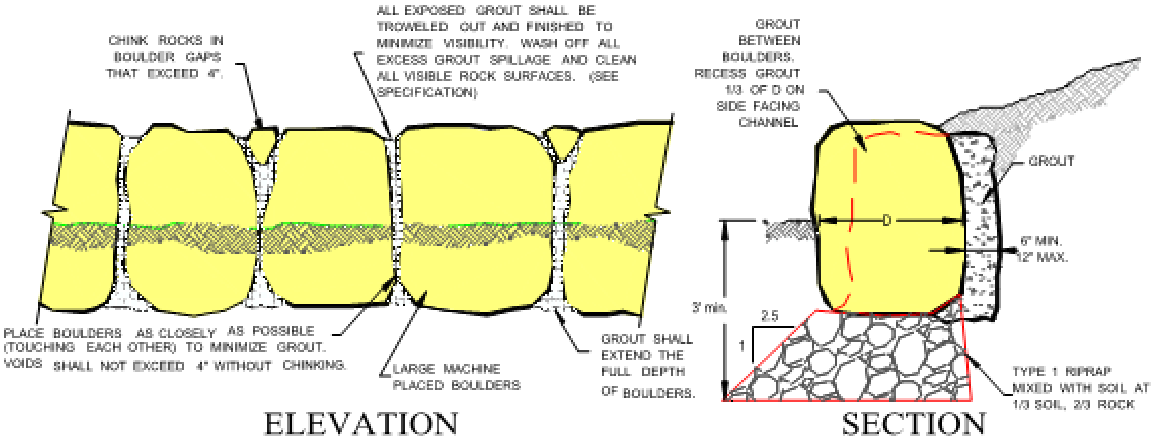
Notes:

1. Soil Riprap details are applicable to sloped areas. Refer to the site plan for actual locations and limits.
2. Mix uniformly 65% riprap by volume with 35% of approved soil by volume prior to placement.
3. Place stone-soil mix result in securely interlocked rock at the design thickness and grade. Compact and level to eliminate all voids and rocks projecting above design riprap top grade.
4. Crimp or tackify much or use approved hydro-mulch as called for in the plans and specifications.

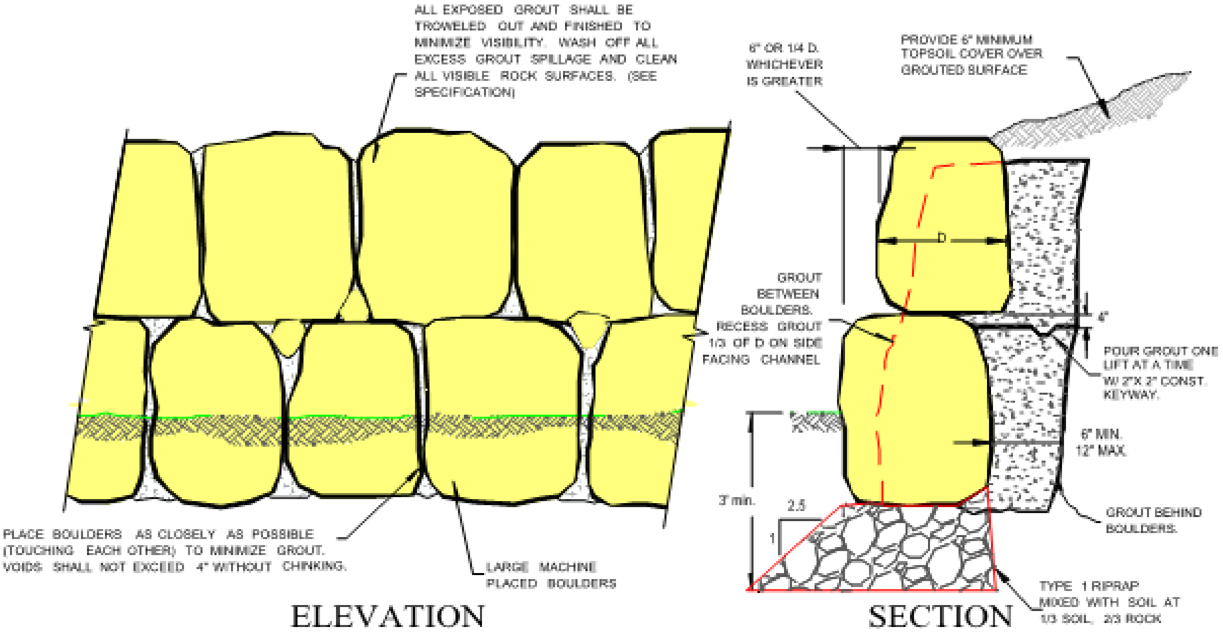
Figure OC-13: Detail – Boulder Edged Low-Flow Channel
(UDFCD USDCM 2002)



BOULDER EDGED LOW FLOW CHANNEL CROSS-SECTION



GROUTED BOULDER EDGE DETAIL



GROUTED BOULDER STACKED WALL EDGE

3.5 Bioengineered Channels

Bioengineered channels emphasize the use of vegetative components in combination with structural measures to stabilize and protect stream banks from erosion. The City advocates the integration of bioengineering techniques into drainage planning, design, and construction when the use of such channels is consistent with the City's policies concerning flow carrying capacity, stability, maintenance, and enhancement of the urban environment and wildlife habitat. The following discussion on bioengineered channels interfaces closely with Section 3.2, Composite (Wetland Bottom) Channels, and Section 3.6, Natural Channels. Designers are encouraged to read Section 3.2, Section 3.5, and Section 3.6, concurrently. In addition, because bioengineered channels require some structural assistance to maintain stability in urban settings, the designer should be familiar with the design of drop structures as discussed in FHWA's *Hydraulic Engineering Circular No. 14, 3rd Edition (HEC-14 2006).*

3.5.1 Components

Vegetation is the basic component of what is known as "bioengineering" (Schiechtl 1980). Schiechtl (1980) states that, "bioengineering requires the skills of the engineer, the learning of the biologist and the artistry of the landscape architect."

It has been hypothesized that vegetation can function as either armor or indirect protection, and, in some applications, can function as both simultaneously (Biedenharn, Elliot, and Watson 1997 and Watson, Biedenharn, and Scott 1999). Grassy vegetation and the roots of woody vegetation may function as armor, while brushy and woody vegetation may function as indirect protection; the roots of the vegetation may also add a degree of geotechnical stability to a bank slope through reinforcing the soil (Biedenharn, Elliot, and Watson 1997 and Watson, Biedenharn, and Scott 1999), but these premises have not yet been technically substantiated through long-term field experience in urban settings. Each species of grass or shrub has differing ecological requirements for growth and differing characteristics such as root strength and density. Species shall be selected based on each site's individual characteristics. Bioengineered channels must be designed with care and in full recognition of the physics and geomorphic processes at work in urban waterways and changing watersheds. Representative components of bioengineered channels include:

1. Planted riprap
2. Planted, grouted boulders
3. Turf reinforcement mats
4. Brush layering

5. Fiber rolls
6. Fascines
7. Live willow stakes (with and without joint plantings in soil filled rock)
8. Live plantings in conjunction with geo-textile mats
9. Wide ranges of planting of wetland and upland vegetation
10. Wrapped soil lifts for slope stability

See Figure OC-13 through Figure OC-15 for more guidance.

3.5.2 Applications

Bioengineered channels are applicable when channel designs are firmly grounded in engineering principles and the following conditions are met:

1. Hydrologic conditions are favorable for establishment and successful growth of vegetation.
2. Designs are conservative in nature, and bioengineered features are used to provide redundancy.
3. Maintenance responsibilities are clearly defined.
4. Adequate structural elements are provided for stable conveyance of the major runoff flow.
5. Species are selected based on individual site characteristics.

3.5.3 Bioengineering Resources

The purpose of this section is to provide the designer with an overview of bioengineering and basic guidelines for the use of bioengineered channels on major drainage projects within the City. There are many sources of information on bioengineering that the designer should consult for additional information when planning and designing a bioengineered channel. Some such resources are: Watson, Biedenharn, and Scott 1999; USFISRWG 1998; Riley 1998; and Biedenharn, Elliot, and Watson 1997. An expert in the design and layout of bioengineering channels should be consulted when attempting such channel design work within the City.

3.5.4 Characteristics of Bioengineered Channels

The following characteristics are generally associated with bioengineered channels:

1. Their design must address the hydrologic changes associated with urbanization (increased peak discharges, increased runoff volume, increased base flow, and increased bank-full frequency).

These changes typically necessitate the use of grade control structures. In the absence of grade control structures, pure bioengineered channels will normally be subject to bed and bank erosion; channel instability; and degradation.

2. In addition to grade controls, most bioengineered channels require some structural methods to assist the vegetation with maintaining channel stability. Examples include buried riprap at channel toes and at outer channel banks (see Figure OC-14, Figure OC-16 and Figure OC-15).
3. The designer must ensure that there will be sufficient flow in the channel (or from other sources, such as locally high groundwater) to support the vegetation. A complicating factor is that, in newly developing areas, base flows will *not* be present; whereas, if the tributary drainage area is large enough, base flows will often materialize after substantial urbanization has occurred. Therefore, it is important to match the channel stabilization technique to the water available at the time of construction, whether naturally or from supplemental water sources.
4. The extent to which vegetative techniques for channel stabilization will need to be supplemented with structural measures is a function of several channel factors:
   a) Slope
   b) Maximum velocity during 5-year event
   c) Maximum velocity during 100-year event
   d) Froude number during 5-year event
   e) Froude number during 100-year event
   f) Tractive force
   g) Sinuosity
   h) Timing of period of construction relative to the growing season
   i) Other site-specific factors

In general, slight channel slopes, lower velocities, lower Froude numbers, lower tractive force values, and higher sinuosity are conducive to channel stabilization approaches that emphasize bioengineering. These factors indicate that park-like settings (areas of open space, parks, office parks, etc.) are often conducive to bioengineered projects because they provide space for the channel to have a meander pattern that increases flow length and decreases channel slope, velocities, and tractive forces.

A technique that can be utilized is stabilization of the outer banks of a defined low-flow channel to withstand the major storm. Within the defined low-flow channel, base flows and small storm flows can then assume their own flow path (meander pattern). This pattern can either be pre-established (with a “pilot” channel) or the flows can move freely from one side to the other of the hardened low-flow channel, thereby establishing their own pattern.

Figure OC-13 shows examples of details for boulder toe protection (grouted and ungrouted, for one- and two-boulder high toe walls) that can be used to define a hardened, low-flow channel within which base flows and small storm flows can freely meander. Boulders shall be placed on a Type 1 riprap foundation, and boulders shall be aligned so that they are wider than they are tall. Boulders should be placed so that the top of the toe protection wall is flat. If stacking is stable, grouting may not be necessary. In areas where the channel is easily accessible to the public, the top row of boulders may be grouted in place so that vandals cannot remove them.

3.5.5 Advantages of Bioengineered Channels

Public reaction to bioengineered channels is generally favorable. In contrast to major drainageway stabilization projects that focus on structural measures, such as concrete-lined or riprap-lined channels, bioengineered channels:

1. Appear more natural in character and, often, more like a channel prior to urbanization. When post-urbanization hydrology permits, riparian areas may be created where there previously was little vegetation. Also, wetlands can often be created in conjunction with bioengineered channels.
2. Have a “softer” appearance and are generally judged by most to be more aesthetic.
3. Are often found where space is not a limitation, such as in public parks and open space areas.
4. Generally, provide and/or enhance wildlife habitat.
5. Provide other benefits such as passive recreational opportunities for the public (like bird watching), open space creation/preservation, potentially water temperature moderation, and/or water quality enhancement.
6. Create a living system that may strengthen over time.
7. Can facilitate obtaining 404 permits.

3.5.6 Technical Constraints

The following constraints are associated with bioengineered channels:

1. There is only limited experience to rely on for successful design of urban channels. The majority of the experience with bioengineering techniques relates to channels in nonurban settings.
2. Careful species selection that reflects the site’s soils and water availability characteristics is essential to ensure survivability of the vegetation chosen for the channel.
3. A basic design criterion within the City is to demonstrate channel stability during the major (100-year) storm to ensure public safety and property protection within urban areas. There is little

evidence (locally, regionally, or nationally) as to whether pure bioengineered channels can withstand 100-year (or lesser) flood forces.

4. Significant space can be required for bioengineered channels, yet space is often at a premium in urban areas.
5. Bioengineered facilities can be more expensive than their traditional counterparts.
6. Bioengineered channels can be maintenance intensive, particularly in their early years.
7. During the early years while the vegetation is becoming established, if a significant storm occurs, the probability of significant damage to the facility and adjacent infrastructure and properties (i.e., economic loss) is high.

Additional potential constraints of vegetative stabilization methods are summarized by Biedenharn, Elliot, and Watson (1997), as follows:

- Even well executed vegetative protection cannot be planned and installed with the same degree of confidence, or with as high a safety factor, as structural protection. Vegetation is especially vulnerable to extremes of weather, disease, insects, and inundation before it becomes well established.
- Most vegetation has constraints on the season of the year that planting can be performed.
- Growth of vegetation can cause a reduction in flood conveyance or erosive increases in velocity in adjacent un-vegetated areas.
- Vegetation can deteriorate due to mismanagement by adjacent landowners or natural causes.
- Trunks of woody vegetation or clumps of brushy vegetation on armor revetments can cause local flow anomalies, which may damage the armor.
- Large trees can threaten the integrity of structural protection by root invasion; by toppling and damaging the protection works; by toppling and directing flow into an adjacent unprotected bank; or by leaving voids in embankments due to decomposition.
- Roots can infiltrate and interfere with internal bank drainage systems or cause excess infiltration of water into the bank.

Many of these problems may be avoided through selection of the appropriate type and species of vegetation. Such selections and expert advice must be obtained from qualified individuals in re-vegetation and bioengineering. Invasion by other species is quite likely over the years the bioengineered channel is in operation.

3.5.7 Design Guidelines

To provide the designer with guidelines for the applicability of bioengineered channels, a comparison of hydraulic characteristics is provided in Table OC-17 for four types of channels, ranging from a fully bioengineered channel to a structural channel. To allow for growth of vegetation and accumulation of sediment, outfalls into bioengineered channels shall be 2 feet above the channel invert.

Table OC-17: Guidelines for Use of Various Types of Channels

(UDFCD USDCM 2002)

Note: All channel types typically require grade control structures.

Design Parameter	Fully Bioengineered Channel	Bioengineered Channel Including Structural Elements	Structural Channel With Bioengineered Elements	Structural Channel
Maximum Slope	0.2%	0.5%	0.6%	1.0%
Is base flow necessary?	Yes	Yes	Yes	No
V_{max} for $Q_{5\text{-year}}$*	3.5 ft/sec (2.5)	4.0 ft/sec (3.0)	5.0 ft/sec (3.5)	**
V_{max} for $Q_{100\text{-year}}$*	5.0 ft/sec (3.5)	6.0 ft/sec (4.5)	7.0 ft/sec (5.0)	**
$Fr_{5\text{-year}}$	0.4 (0.3)	0.6 (0.4)	0.7 (0.5)	**
$Fr_{100\text{-year}}$	0.4 (0.3)	0.8 (0.5)	0.8 (0.5)	**
Maximum tractive force (100-year event)	0.30 lb/ft^2	0.60 lb/ft^2	1.00 lb/ft^2	1.30 lb/ft^2
Maximum sinuosity	1.6	1.2	1.2	1.0

* Values presented for both non-erosive and erosive soils. Erosive soil values are in parenthesis ( ).

** With a purely structural channel, such as a reinforced concrete channel, allowable velocities and allowable Froude numbers, *Fr*, are based on site-specific design calculations.

3.6 Natural Channels

Natural waterways in the City of Bella Vista sometimes have steep, almost vertical stream banks with eroding banks and bottoms. On the other hand, many natural waterways exist in urbanized and to-be-urbanized areas, which have mild slopes, are reasonably stable, and are not currently degrading. If the channel will be used to carry storm runoff from an urbanized area, it can be assumed that the changes in the runoff regime will increase channel erosion and instability. Careful hydraulic analysis is needed to address this projected erosion. In most cases, stabilization of the channel will be required. Stabilization using the bioengineering techniques described in Section 3.5 of this chapter has the advantage of preserving and even enhancing the natural character and functions of the channel. Some structural stabilization measures will also be required in combination with the bioengineered stabilization measures.

In the Bella Vista area, most natural waterways will need drops and/or erosion cutoff check structures to maintain a mild channel slope and to control channel erosion. Typically, these grade control structures are spaced to limit channel degradation to what is expected to be the final stable longitudinal slope after full urbanization of the tributary watershed. Slopes have been observed to range from 0.30% to 1.5%, within Benton County, depending on the watershed size and channel soils. Whenever feasible, natural channels shall be kept in as near a natural condition as possible by limiting modifications to those necessary to protect against the destabilizing hydrologic forces caused by urbanization.

Investigations needed to ensure that the channel is stable will differ for each waterway. However, it will be necessary to measure existing cross-sections; investigate the bed and bank material; determine soil particle size distribution; and study the stability of the channel under future conditions of flow. At a minimum, the designer should consider the concept of the stable channel balance discussed in Section 1.5.2 of this chapter; complete tractive force analysis; and apply the Leopold equations to evaluate channel stability and changes in channel geometry. Oftentimes, more sophisticated analysis will be required. When performing stability and hydraulic analysis, supercritical flow normally does not exist in natural-earth channels. During backwater computations, check to ensure that the computations do not reflect the presence of consistent supercritical flow (Posey 1960). Because of the many advantages of natural channels to the community (e.g., preservation of riparian habitat, diversity of vegetation, passive recreation, and aesthetics), the designer should consult with experts in related fields as to method of development. Nowhere in urban hydrology is it more important to convene an environmental design team to develop the best means for using a natural waterway. It may be concluded that park and greenbelt areas should be incorporated into the channel design. In these cases, the usual rules of freeboard, depth, curvature, and other rules applicable to artificial channels often will need to be modified to better suit the multipurpose objectives. For instance, there are advantages that may accrue if the formal channel is designed to overtop, resulting in localized flooding of adjacent floodplain areas that are laid out for the purpose of being inundated during larger (i.e., > 10-year) flood events. See the Chapter 6 – *Detention Design*.

The following design criteria are required when evaluating natural channels:

1. The channel and overbank floodplain shall have adequate capacity for the 100-year flood.
2. A water surface profile shall be defined in order to identify the 100-year floodplain, to control earthwork, and to build structures in a manner consistent with Bella Vista's floodplain regulations and ordinances.
3. Use roughness factors (*n*) representative of un-maintained channel conditions for analysis of water surface profiles. Roughness factors for a variety of natural channel types are presented in Table OC-7.
4. Use roughness factors (*n*) representative of maintained channel conditions to analyze effects of velocities on channel stability. Roughness factors for a variety of natural channel types are presented in Table OC-7.
5. Prepare plan and profile drawings of the channel and floodplain.
6. Provide erosion-control structures, such as drop structures or grade-control checks, to control channel erosion and/or degradation as the tributary watershed urbanizes.
7. Outfalls into natural channels shall be 2 feet above the channel invert to account for vegetation and sediment accumulation. The engineer should visit the site of any outfalls into natural

drainageways to examine the actual ground surface condition.

Figure OC-14: Live Willow Staking for Bare Ground and Joint Installation (UDFCD USDCM 2002)

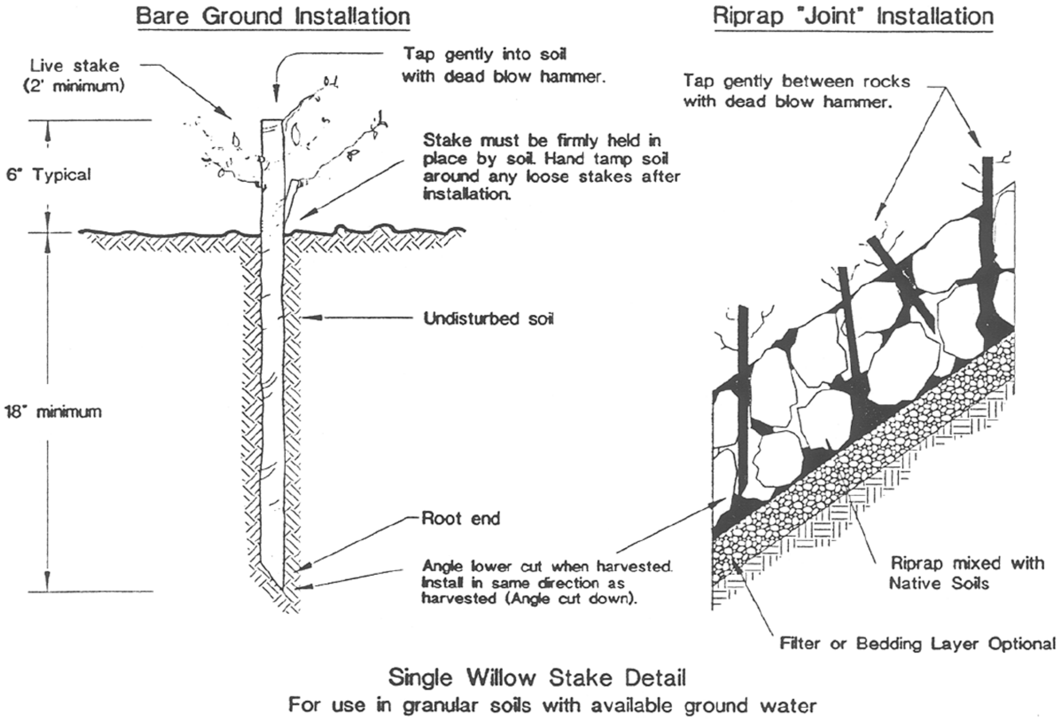
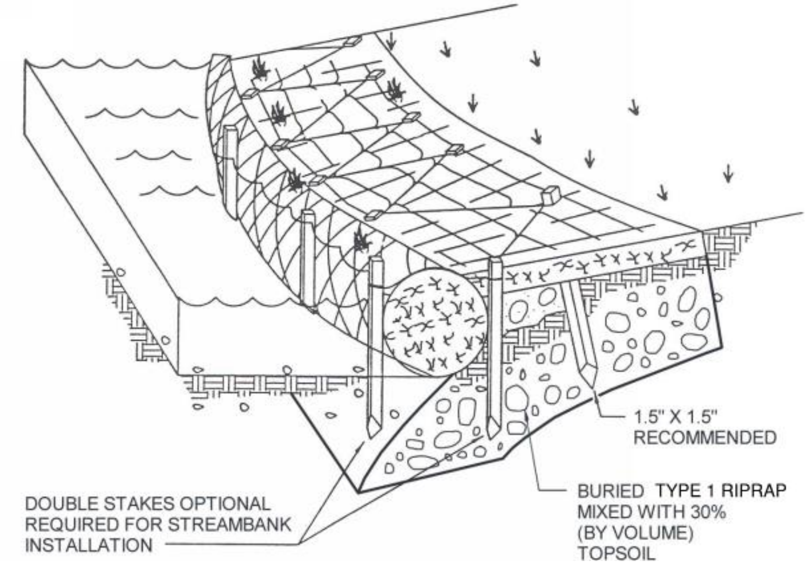


Figure OC-15: Fiber Roll (UDFCD USDCM 2002)

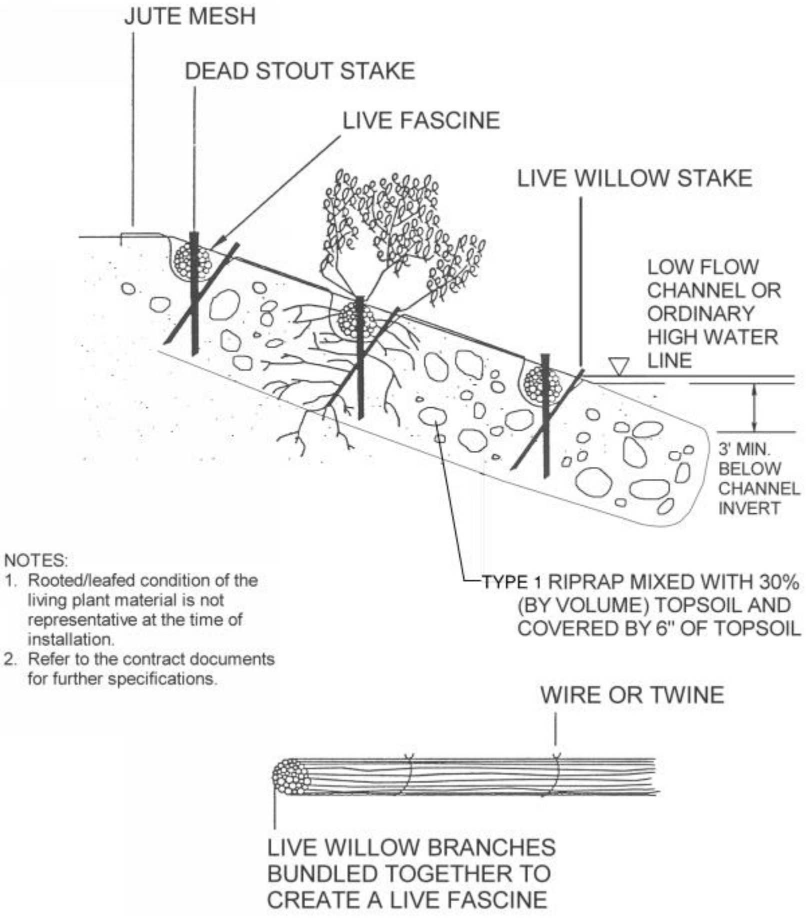


Notes:

1. Length of stake determined by the substrate.
2. Refer to contract documents for further details.

Reprinted from Salix Applied Earthcare, Erosion Draw 2.0, 1996

Figure OC-16: Fascine in Conjunction with Jute Mesh Mat (UDFCD USDCM 2002)



NOTES:

1. Rooted/leafed condition of the living plant material is not representative at the time of installation.
2. Refer to the contract documents for further specifications.

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