MAJOR DRAINAGE

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1.0 INTRODUCTION

1.1 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.

The major drainage system may include many features such as natural and artificial channels, culverts, long underground conduits and outfalls, streets, property line drainage easements, and others. It is closely allied to, but separate from, the initial drainage system consisting of storm sewers, curbs and gutters, swales, and minor drainageways. The two separate systems should generally be planned together. In many cases, a good major system can reduce or eliminate the need for an underground storm sewer system. An ill-conceived major system can make a storm sewer system very costly. The 2-, 5- or 10-year or other smaller runoff event can flow in the major system, but only a portion of the 100-year and larger runoff events will flow in the initial drainage system.

Photograph MD-1—An engineered wetland channel can serve as a filter for low flows and yet carry the major flood event without permanent damage.

While the primary function of a major drainageway is conveyance of runoff, many design decisions contribute to the role of the drainageway in the urban environment in terms of stability, multiple use benefits, social acceptance, aesthetics, resource management, and channel maintenance. It is important for the engineer to be involved from the very start of a land development project, so that the criteria in this *Manual* have bearing on the critical planning decisions involved in route selection for 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 to use to the benefits derived to the community for years to come.

1.2 Types of Major Drainage Channels

The types of major drainage channels available to the designer are numerous, depending upon good hydraulic practice, environmental considerations, sociological/community impact and needs, permitting limitations, and basic project requirements. Section 3.3.1 describes in detail the following types of channels engineers can consider as potential major drainage channels in urban areas and then select the ones that address the considerations listed above the best:

- Natural channels
- Grass-lined channels
- Composite channels
- Concrete-lined channels
- Riprap-lined channels
- Bioengineered channels
- Channels with manufactured liners
- Boatable channels

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.

1.3 Overview of Chapter

This chapter addresses the major topics related to major drainage design, beginning with essential background on the issues of major drainage planning and engineering (Section 1.4) and fluvial geomorphology (Section 1.5). Section 2.0 addresses planning for major drainage systems, including route selection and requirements for drainage master planning. General open channel hydraulics and preliminary design criteria are presented in Section 3.0. It is assumed that the designer is 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 4.0 contains specific design criteria for a variety of channel types and includes example calculations, typical cross sections, and other representative design details. Sections 5.0 and 6.0 address rectangular conduits and large pipes, respectively, and Section 7.0 provides information on the use of riprap and boulders for major drainage applications. Section 8.0 addresses sediment.

1.4 Issues in Major Drainage Planning and Engineering

The planner and engineer have great opportunities when working on major channels to help provide a better urban environment for all citizens. The challenge is particularly great for those having the opportunity to plan and design works in the core areas of cities. The most fundamental function of a major drainageway is conveyance of the major storm runoff event, and an important characteristic is its 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. Urbanization in the Denver metropolitan area 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 the drainageway in the urban environment, in terms of multiple use benefits, social acceptance, aesthetics, and resource management. The choices of the type and layout of the major drainage system and the type of flow conveyance elements are of prime importance.

Types of major drainageways can generally be characterized as open (i.e., open channel) or closed (i.e., below-ground rectangular conduits and large pipes). Open channels for transporting major storm runoff are more desirable than underground conduits in urban areas, and use of such channels is encouraged. Open channels 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. Channel layout affords many opportunities for creation of multiple uses in addition to the channel's fundamental function of conveyance of the major event. Photograph MD-2 illustrates some of the multiple uses/benefits of well-planned major drainageways. Open channels are also usually less costly than closed conduits and they provide a higher degree of flood routing storage.

The function of open channels does not depend on a limited number of inlet points. Getting storm flows into a closed coduit system can be problematic since blockage of inflow points can be problematic and has been observed to occur during larger runoff events. Public safety is a major concern with closed conduits and the record of life loss is well documented when individuals were swept into a conduit.

Disadvantages of open channels include higher right-of-way needs and maintenance costs; however, maintenance of failed or failing closed conduits can be much more expensive. Careful planning and design can minimize the disadvantages and increase the benefits of open channel drainageways.

Photograph MD-2—Well-planned major drainageways provide biological diversity, recreational opportunities, and aesthetic benefits in addition to flood conveyance.

The choice of the type of open channel is a critical decision in planning and design of major drainageways. The ideal channel is a stable natural one carved by nature over a long period of time that can remain stable after urbanization. The benefits of such a channel can often include any or all of the following:

1. Relatively low-flow velocities sometimes resulting in longer concentration times and lower downstream peak flows.

2. Channel storage that tends to decrease peak flows.

3. Reasonable maintenance needs when the channel is somewhat stabilized.

4. A desirable greenbelt, which can support urban wildlife and recreation, adding significant social and environmental benefits. The REVEGETATION chapter provides guidance on vegetation selection, design, planning and maintenance for wetland and upland settings along naturalized man-made or stabilized natural channels.

5. Support of a variety of processes that preserve and/or enhance water quality, ranging from microbial activity in the bed and water column to the pollution prevention afforded by a stable channel's resistance to erosion.

Photograph MD-3—Integrating major drainageways into neighborhoods is critical for success.

Generally, the closer an artificial channel's character can be made to that of a natural channel, the more functional and attractive the artificial channel will be. 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.

Design of the major drainage system should consider the features and functions of the existing drainage system. Natural drainageways should be used for storm runoff waterways when feasible, and floodplains along drainageways should be preserved when feasible and practicable. Open channel planning and design objectives are often best met by using natural-like vegetated channels, which characteristically have slower velocities and large width-to-depth ratios. Efforts must be made to reduce peak flows and control erosion so that the natural channel regime is preserved, to the extent practical.

1.5 Fluvial Geomorphology

Any person who has witnessed the rise in stage of a river during spring snowmelt or who has observed the swelled banks of a river after an intense thunderstorm has a sense of the dynamic nature of waterways. Relatively simple hydraulic calculations can be performed to define flow conditions for a given set of specific, well-defined parameters; these techniques have been a highly effective basis of open channel design for many years. Walking along the bank of a channel, however, one quickly realizes that the actual behavior of the channel is far more complex than a simple, unchanging geometric cross section and a battery of design flow conditions. Fluvial geomorphology provides an approach to understanding the dynamic nature of a stream and the interactions between the water and the channel.

A drainage system within a watershed involves flowing water or 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 stream channels behave in a complex manner 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.

1.5.1 Stream Channel Characterization

At the start of the design process for on-site major drainageways, the designer should carefully characterize all existing channels on a reach-by-reach basis, documenting parameters including bank slope, bank cover, trees, bank line, sediment deposits, and scour areas in addition to geomorphic characteristics related to channel planform and hydraulics, such as sinuosity, riffle characteristics, cross-sectional geometry, and slope. For larger, complex channels, assistance from a specialist in stream channel behavior is recommended. Biologists can provide valuable input, as well, regarding existing wetland and upland vegetation, wildlife habitat, revegetation considerations, and other factors that indirectly relate to channel stability considerations.

Methods of channel assessment should utilize aerial photography, interviews with nearby residents, master plans, and other information available for the existing channel. Inspection of channels in areas of urbanization that, prior to development, had similar characteristics to the area planned for development can provide valuable foresight into channel changes likely to occur because of urbanization. By understanding channel behavior historically, currently, and in the future, the designer will focus on the optimal strategies for attaining channel stability. Detailed information regarding field data to collect for channel assessment is provided by Leopold (1994).

1.5.2 Effects of Urbanization on Stream Channels

In response to urbanization, stream channels can undergo substantial changes, especially 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 (this practice is discouraged by the District); (3) reduction in sediment bed load 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. Photograph MD-4 illustrates severe channel degradation in response to increased flows caused by urbanization.

Photograph MD-4—Channel degradation in an unstable channel.

To fully evaluate the proper channel morphological processes when undertaking a basic design or protective measure project, it is necessary to have some knowledge of channel stability concepts. The normal objective of channel stability evaluation is identification of principal channel hydraulic parameters influencing the stability of the channel. After identifying these parameters under existing channel conditions, the values of these parameters under future conditions are estimated. For areas undergoing urbanization, one of the most important changes is an increase in the volume, frequency, and flow rates of water in main channels. Stability analysis is then performed based on hydraulic parameters for anticipated future conditions, and stabilization measures are planned to minimize potential channel erosion under future conditions. There are a number of quantitative methods of channel stability analysis available to the designer including allowable velocity methods (Fortier and Scobey 1926), tractive force calculations, and Leopold channel configuration relationships (Leopold 1994), among others.

1.5.3 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. In this case, 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.

An illustration, shown as Figure MD-1 (from USFISRWG 1998 [originally from Lane 1955a]), provides a visual depiction of a stable channel balance based on the relationship proposed by Lane (1955a) for the equilibrium concept whereby:

$$Q_w S \propto Q_s D_{50} \quad \text{(MD-1)}$$

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 (mm)

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 either bed material size or sediment load, or both.

1.5.4 References for Additional Information

Copious information exists on fluvial geomorphology ranging from the pioneering works of Lane, Leopold, and others to more recent compendiums on channel geomorphology and stability. References that may be useful to the designer include:

- *The Importance of Fluvial Morphology in Hydraulic Engineering* (Lane 1955b).
- *Progress Report on Results of Studies on the Design of Stable Channels: A Guide for Planners, Policymakers and Citizens* (Lane 1955a).
- *A View of the River* (Leopold 1994).
- *Restoring Streams in Cities* (Riley 1998).
- *Applied River Morphology* (Rosgen 1996).
- *Stream Corridor Restoration: Principles, Processes, and Practices* (USFISRWG 1998).
- *Sedimentation Engineering* (Vanoni (ed.) 1975).

- *Channel Rehabilitation: Process, Design, and Implementation* (Watson, Biedenharn, and Scott 1999).

Additional references can be found in the reference section of this chapter or in the extensive bibliographies of the references listed above.

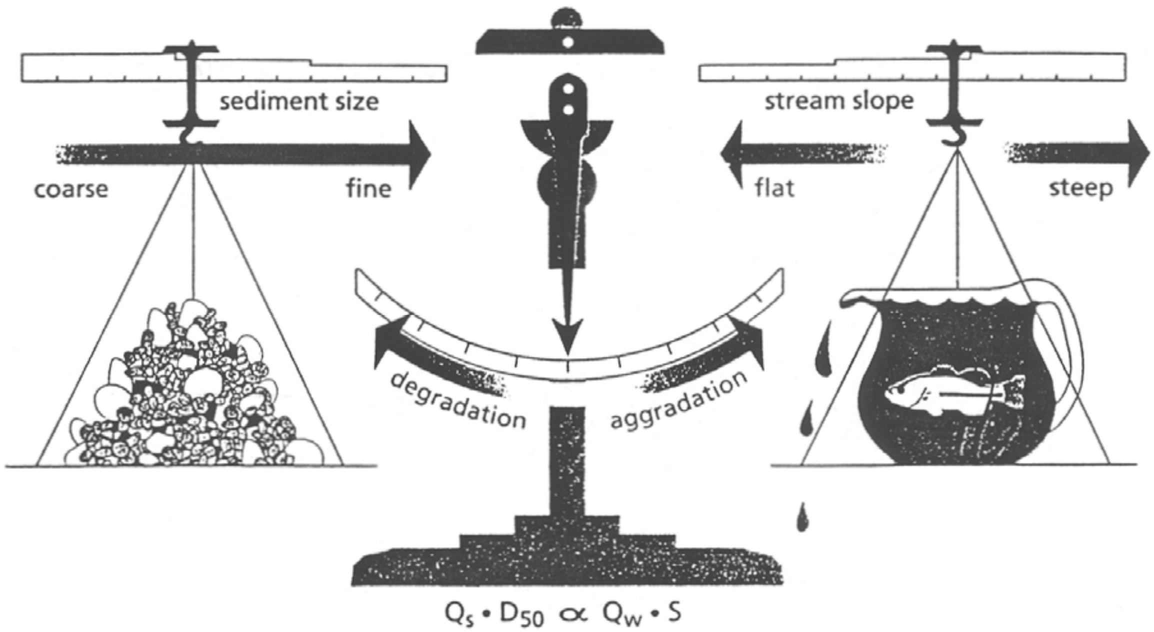


Figure MD-1—Illustration of the Stable Channel Balance Based on the Relationship Proposed by Lane (1955)

Note: This graphical interpretation of Lane's Equation was reprinted from *Applied River Hydrology*, with written permission from Mr. David Rosgen of Wildland Hydrology (and author of the book) in Pagosa Springs, Colorado.

2.0 PLANNING

2.1 General

A major drainage system that is thoughtfully planned can provide adequate conveyance of the major runoff event in addition to other benefits to the urban area that it serves. A basic policy of the District is that the major drainage system, regardless of type, should be capable of conveying water without flooding buildings and remain relatively stable during the major runoff event (e.g., the 100-year flood). A study of the POLICY and PLANNING chapters is suggested to provide a foundation for understanding this section.

By respecting natural drainage patterns and existing floodplains in planning, appropriate major drainageway systems, including natural-like open-channel drainageways, can be created that provide flood capacity, that are stable, cost effective, and environmentally sensitive, and that offer multiple use benefits to surrounding urban areas.

2.2 Impacts of Urbanization and Associated Effects

The hallmark of urbanization is increased imperviousness. Planning of a major drainage system must account for changes in hydrology, hydraulics, and channel stability that urbanization produces. As a result, the design of the major drainage system must be based on fully urbanized conditions to assure adequate capacity for conveyance of the major (e.g., 100-year) flood event. It is also important to recognize that the higher sediment loads during the process of urbanization (during construction) may shift the channel toward an equilibrium state that is different from the desired stable channel balance for the urbanized basin.

2.3 Special Considerations for Semi-Arid Climates

Major drainage planning and design efforts along natural waterways in the Denver area must consider the region's semi-arid climate. Special considerations include:

1. Streams that have historically been ephemeral or intermittent often develop base flow because of the increased volume of water from impervious areas and infiltration of lawn and garden irrigation water, water line leakage, car-wash rinse water, and other factors. In addition, the increase in impervious area from urbanization can result in dramatic increases in the volume, discharge, and frequency of surface runoff, especially relative to base flow (if any), resulting in channel instability.

2. Availability of water for support of vegetation must be evaluated when considering types of major drainage channels utilizing vegetation including grass-lined channels, channels with wetland bottoms, and bioengineered channels. This is especially important for channel types using wetland vegetation since the high productivity of wetland plants

results in a high level of water consumption. See the REVEGETATION chapter for additional information on vegetation selection and water use.

2.4 Route Considerations

A preliminary estimate of the design rate of flow is necessary to roughly approximate the channel or conduit capacity and size. This estimate can be made by comparing to other similar watersheds where unit rates of discharge have been computed, or using the design flow rates published in master plans.

Routing of the outfall is usually a relatively straightforward matter of following the natural valley (thalweg) and defining it on a map. In many urbanized and agricultural areas, however, there is no thalweg, or the thalweg has been filled and/or built upon. For these cases, it is necessary to determine many factors before the route is chosen. Representative items to determine for routing the outfall are discussed below, many of which apply even when the thalweg is defined.

2.4.1 Present Flow Path

Fully examine topographic mapping to determine where the storm runoff would go without any further work or modification to the ground surface.

2.4.2 Historic Flow Path

Determine, by using old mapping and aerial photographs, where the water would have flowed prior to any man-made changes.

2.4.3 Permitting and Regulations

Major drainage planning and design along existing natural channels are multi-jurisdictional processes and, therefore, must comply with regulations and requirements ranging from local ordinances to federal laws. The concept of floodplain regulation recognizes, and is premised upon, governmental responsibility for administration of publicly owned rights-of-way and flood-related prescriptive easements. At the local level, floodplain management is accomplished through zoning ordinances and land use regulations and/or requirements. On a regional level, floodplain management and drainage policies are identified in the POLICY chapter of this Manual.

All construction within the 100-year floodplain must comply with the National Flood Insurance Program (NFIP) regulations. Permits for all development in the 100-year floodplain and the Special Flood Hazard Area (SFHA) must be acquired from local governments. The policy of the District is to encourage the preservation and enhancement of natural floodplains whenever feasible. Filling floodplain fringes is generally discouraged because discharge and flood stoorage capacity in the flood fringe is important and filling tends to increase water surface elevations, velocity of flow, and downstream peak flows. All filling in the floodplain fringe should be undertaken with caution and in accordance with Federal Emergency

Management Agency (FEMA) and local regulations. Modifications to the 100-year floodplain related to the major drainage system must be documented through the FEMA map revision process.

Wetland regulations and permitting issues are also relevant to the major drainage system. A permit under Section 404 of the federal Clean Water Act (CWA) is required for any activities impacting "waters of the U.S. and jurisdictional wetlands." Construction of major drainage improvements along existing natural drainageways typically requires a Section 404 permit from the U.S. Army Corps of Engineers (USACE). In addition, routine maintenance activities along established major drainage channels and in wetlands may also require a Section 404 permit. Always check with the USACE to determine if the proposed channel work or maintenance activities require a 404 permit. In addition to federal wetland regulations, construction of major drainage improvements along existing natural drainageways may be subject to the federal Endangered Species Act. Early and regular discussions and coordination with permitting authorities is encouraged from start through final mitigation activities. Refer to Section 3.3.3 for additional information on permitting.

2.4.4 Public Safety

Public safety is fundamental to the major drainage system. One purpose of the major drainage system is to protect an urban area from extensive property damage and loss of life from flooding. However, there are also "day-to-day" safety considerations in design such as the use of railings at vertical walls and avoiding vertical drops and use of steep side slopes adjacent to public trails.

2.4.5 Public Acceptance

Planning and design are of primary importance in gaining public acceptance. Public acceptance of the major drainage system depends on many factors such as public perception of flood protection, channel aesthetics, right-of-way, open space preservation, and channel maintenance. The use of open channels, especially those utilizing vegetation and other natural material and natural-like planform and morphology can create aesthetic and recreational amenities for the public and often are congruous with community open space goals. The general principle that the closer an artificial channel's character is to that of a natural channel, the better the artificial channel will be, often holds true for public acceptance, as well.

2.4.6 Alternate Routes

Choose various routes on maps and examine them in the field from engineering viewpoints. Also, determine social impacts on neighborhoods and general environmental design restraints.

2.4.7 Maintenance

Identify points of access along alternate routes based on existing and proposed roads and public rights-of-way. Adequate right-of-way is necessary to provide maintenance access for a major drainageway.

2.4.8 Route Costs

Prepare profiles of apparently satisfactory routes and make rough cost estimates of each, using approximations as to character and location of channel or conduit. Include costs of bridges, culverts, drop structures, special structures and facilities, etc.

2.4.9 Recreational Use Potential

Identify areas with potential for recreational use. Factors to consider include proximity to residential areas, access to channel via roads and trails, areas suitable for creation of multi-use areas along channel, and location of potentially hazardous areas.

2.4.10 Environmental Considerations

Examine advantages and disadvantages of routes with an environmental design team normally consisting of an urban planner, biologist, and landscape architect, and, in some cases, an urban sociologist and drainage attorney. Include USACE regulatory personnel in these examinations to identify permitting issues that need to be addressed and to avoid 404 permitting problems later. Choose the best route based upon maximum total advantages and benefits.

2.4.11 Presentation of Choice

A meeting should be held between project sponsors and affected parties to discuss the routes studied and to select the final route. At the same time, the types of channel or conduit being considered should be presented and suggestions or concurrence should be obtained. A dialogue with citizen groups where various alternates are explained is encouraged.

2.4.12 Underground Conduits

Open channels for transporting major storm runoff are more desirable than underground conduits in urban areas because they are closer in character to natural drainageways and offer multiple use benefits. However, right-of-way constraints in urbanized areas (in the case of redevelopment, for example) may necessitate the use of underground conduits. District does not support the practice of putting major drainageways into underground conduits unless there is an overwhelming need to reduce flooding in already developed areas. The primary considerations when selecting underground conduits are public safety concerns of people being swept into them and the fact that underground conduits are extremely susceptible to having their inflow points clogged, especially when equipped with safety or trash racks. Once clogged, they fail to provide the intended flood protection. For this reason, overflow paths should be provided for to have little or no flood damage when the inlet end of a long conduit is clogged.

2.4.13 Two-Stage Channels

In some cases, it may be desirable to distribute the 100-year flow between a formal channel and the adjacent floodplain. These two-stage channels are acceptable as long as they are designed so that velocity and depth criteria stated in this chapter are satisfied for the 100-year event. Freeboard must still be provided between the 100-year water surface profile and the lowest point of building entry or first floor elevation, whichever is lower, and all applicable roadway overtopping criteria must be considered.

2.5 Layout

The approximate centerline should be laid out on topographic mapping and adjustments made for best fit. At a minimum, the following factors should be taken into consideration:

- Land form (including topography and historic and existing thalwegs)
- Right-of-way
- Curvature
- Existing or future streets
- Ability to drain adjacent land

2.5.1 Working Map

The outfall should be surveyed with adequate detail. An aerial photographic contour map with 2-foot contours at a scale of 1 inch to 50 feet or 100 feet is desirable. In the case of an outfall conduit, a centerline field survey often suffices if adequate adjacent conditions are reflected in the survey.

2.5.2 Preliminary Plan and Profile

The existing ground surface, street grades, conflicting utilities, and other pertinent data can be plotted in plan and profile. Grades should be noted and analyzed and thought should be given to hydraulic requirements. Adjustments to the centerline should be made where needed to alleviate problem areas when possible and to provide the maximum total benefits.

2.6 Master Planning or Preliminary Design

The preliminary design portion of the planning phase is second in importance only to route selection and the concept stage. Here major decisions are made as to design velocities, location of structures, means of accommodating conflicting utilities, and potential alternate uses in the case of an open channel. Decisions on the use of downstream detention storage or upstream storage also need to be made. The planning and preliminary design should include evaluation of the full spectrum of channel improvements for application in each major drainage management project.

2.6.1 Criteria for Final Hydrology

The characteristics of the outfall are defined after the master planning is underway. At this time, the final hydrological analyses should be performed for additional refinements and use as the proposed conveyance geometries can affect the peak flows in the total system.

2.7 The Master Plan

The master major drainage plan must both provide thorough attention to engineering detail and be suitable for day-to-day use by local and regional governmental administrators. Drainage facility designers should check relevant major drainageway/outfall master plans to assure that the facilities they are designing are consistent with the intent of these master plans. The significant parts of a master plan are described below.

2.7.1 Report

The report shall include a description of the basin, the present and future ultimate development (both on-site and in the upstream drainage area), rainfall data, unit hydrograph derivations, major runoff quantities, engineering criteria used in planning, alternate plans, environmental design considerations, legal opinions, and recommendations. The ability of the major drainage system to serve the total tributary basin must be demonstrated.

2.7.2 Drawings

The drawings shall be prepared on full-size plan and profile sheets at a scale of 1 inch to 50, 100, 200, or even 400 feet, as appropriate for the plan being developed. Detail must be shown in regard to bottom elevations, the approximate hydraulic grade line, bridge and culvert opening criteria, and typical cross sections. Adequate information is needed to provide a guide to land acquisition.

3.0 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.

3.1 General Open Channel Flow Hydraulics

Whether using a natural or constructed channel, hydraulic analyses must be performed to evaluate flow characteristics including flow regime, water surface elevations, velocities, depths, and hydraulic transitions for multiple flow conditions. Open channel flow analysis is also necessary for underground conduits to evaluate hydraulics for less-than-full conditions. Hydraulic grade lines and energy grade lines should 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. Many excellent references address open channel hydraulics in great detail, including Chow (1959), Daugherty and Franzini (1977), and King and Brater (1963). Water surface profile computations are not addressed herein, and the reader is referred to these references for discussion of this topic.

3.1.1 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*—conditions at any point in a stream remain constant with respect to time (Daugherty and Franzini 1977).
- *Unsteady flow*—flow conditions (e.g., depth) vary with time.
- *Uniform flow*—the magnitude and direction of velocity in a stream are the same at all points in the stream at a given time (Daugherty and Franzini 1977). 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*—discharge, depth, or other characteristics of the flow change along the course of the 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*.

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

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \quad \text{(MD-2)}$$

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 MD-2, where V is velocity (ft/sec).

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

$$Q = \frac{1.49}{n} b y^{5/3} S^{1/2} \quad \text{(MD-3)}$$

$$y = \frac{Q^{0.6} n^{0.6}}{1.27 b^{0.6} S^{0.3}} \quad \text{(MD-4)}$$

$$S = \frac{(Qn)^2}{2.2 b^2 y^{3.33}} \quad \text{(MD-5)}$$

Since solution of Equation MD-2 for depth is iterative, a number of techniques are useful to quickly obtain the solution without having to perform iterations. Figure MD-2 can be used to determine normal depth graphically based on convenient dimensionless parameters. In addition, the ***UD-Channels*** spreadsheet available through the www.udfcd.org website can be used to perform normal flow calculations for trapezoidal channels and can help with the design of such channels. Example MD-1, provided at the end of this chapter, illustrates application of this spreadsheet for finding the normal depth of a trapezoidal channel.

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 ignored conditions the flow actually has depths that can be considerably different. Uniform flow computation provides only an approximation of what will occur

3.1.2 Roughness Coefficients

When applying Manning's Equation, the choice of the roughness coefficient, n, is the most subjective parameter. Table MD-1 provides guidance on values of roughness coefficients to use for channel design. Both maximum and minimum roughness coefficients should 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, use Retardance C for finding Manning's n for finding the depth in a mature channel and Retardance D for finding the controlling 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.

For additional information on roughness coefficients, the reader is referred to the U.S. Geological Survey Water Supply Paper 1849 (Barnes, Jr. 1967).

3.1.3 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:

$$F_r = \frac{V}{\sqrt{gd}} \qquad \text{(MD-6)}$$

in which:

V = mean velocity (ft/sec)

g = acceleration of gravity = 32.2 ft/sec²

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

Table MD-1—Roughness Coefficients ("*n*") for Channel Design

(After Chow 1959)

Channel Type	Roughness Coefficient (*n*) Minimum	Typical	Maximum
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. Concrete			
a. Trowel/float finish	0.011	0.015	0.016
b. Shotcrete	0.016	0.020	0.025
2. 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
3. Wetland Bottom Channels		See Figure MD-9a	
4. Grass-Lined Channels and Swales		See Figure MD-9b	

When F_r = 1.0, flow is in a *critical* state. When F_r < 1.0, flow is in a *subcritical* state. When F_r > 1.0, flow is in a *supercritical* state. The following sections describe these flow regimes and associated criteria for channel design.

The *specific energy* of flow in a channel section is defined as the energy per pound of water measured with respect to the channel bottom. Specific energy, E (expressed as head in feet), is given by:

$$E = y + \frac{V^2}{2g} = y + \frac{Q^2}{2gA^2} \qquad \text{(MD-7)}$$

in which:

y = depth (ft)

V = mean velocity (ft/sec)

g = acceleration of gravity = 32.2 ft/sec^2

Q = discharge (cfs)

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

For all subcritical channels, check the Froude number using the *minimum* value of n. When performing hydraulic computations for grassed channels, the n values for the 0.1-foot to 1.5-feet flow depth range 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 values are more appropriate since flows will tend to lay the grass down to form a smoother bottom surface.

3.1.3.1 Critical Flow

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

1. The specific energy is a minimum for a given discharge.
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 MD-6.)
6. The velocity of flow in a channel of small slope is equal to the celerity 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. A flow at or near the critical state may not be stable. 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.

To simplify the computation of critical flow, dimensionless curves have been given for rectangular, trapezoidal, and circular channels in Figure MD-3. Critical velocity, V_c, can be calculated from the critical hydraulic depth, d_c. For a rectangular channel, the flow depth is equal to hydraulic depth, ($y_c = d_c$), and the critical flow velocity is:

$$V_c = \sqrt{g y_c} \qquad \text{(MD-8)}$$

In addition, the **Critical** worksheet from the UD-Channels Spreadsheet performs critical depth calculations.

3.1.3.2 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.

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

A concrete-lined channel should 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, a channel with a wetland bottom, or a bioengineered channel is normally preferable in the Denver region. Do not design 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. 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.

3.1.3.3 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 such a channel. 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 joints can cause rapid deterioration of the joints, which may cause a complete failure of the channel. In addition, high velocity flow at cracks or joints creates an uplift force by creating zones of flow separation with negative pressures and converts the velocity head to pressure head under the liner which can virtually tear out concrete slabs. 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 Denver region, all channels carrying supercritical flow shall be lined with continuously reinforced concrete linings, both longitudinally and laterally. There shall be no diminution of wetted area cross section at bridges or culverts. Freeboard shall be adequate to provide a suitable safety margin. Bridges or other structures crossing the channel must be anchored satisfactorily to withstand the full dynamic load that might be imposed upon the structure in the event of major trash plugging.

The concrete linings must be protected from hydrostatic uplift forces that are often created by a high water table or momentary inflow behind the lining from localized flooding. A perforated underdrain pipe, designed to be free draining, is required under the lining. For supercritical flow, minor downstream obstructions do not create any backwater effect. Backwater computation methods are applicable for computing the water surface profile 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. Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and should be avoided.

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. Because of field construction limitations, the designer should use a Manning's n roughness coefficient equal to 0.013 for a well-trowelled concrete finish. Other finishes should have proportionately larger n values assigned to them.

3.2 Preliminary Design Criteria

3.2.1 Design Velocity

Minimum and maximum velocities must be considered in the design of major drainage systems. From structural and stability standpoints, maximum velocities are of concern; however, minimum velocities should 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 or other velocity controls will be necessary to control erosion and maintain channel stability. *Subcritical* flow is desirable since the velocity for *subcritical* flow is less than that of critical or *supercritical* flow for a given discharge. Froude number criteria also restrict velocity.

The flow velocity during the major design storm (i.e., 100-year) must recognize the scour potential of the channel, whether natural, grassed, bioengineered, riprapped or concrete-lined. Average velocities need to be determined using backwater calculations, which account for water drawdowns 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 should not exceed velocities and Froude numbers given in Table MD-2 for non-reinforced channel linings and, in general, should 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 4.0 of this chapter for various types of open channels.

For estimating maximum velocities for erosive or hazard considerations or localized scour in a channel, relying only upon the HEC-2 or HEC-RAS (USACE 1991, 1995) outputs for the cross section is not acceptable. Instead, more detailed hydraulic analysis of the specific cross section, which accounts for variable velocities across the channel, is necessary.

3.2.2 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 flow is occurring (USBR 1984). As criteria, the design depth of flow for the major storm runoff flow during a 100-year flood should not exceed 5.0 feet 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.

3.2.3 Design Slopes

3.2.3.1 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 should not be so steep as to result in a Froude number greater than 0.5 or 0.8, depending on soil erodibility characteristics (see Table MD-2), for the 100-year event. Slopes for channels with vegetative linings should not exceed 0.6% and should be less than 1% for channels with reinforced concrete linings. For steep-gradient drainageways, drop structures are necessary to meet slope criteria. 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 incorporating meanders can be used to satisfy slope criteria, potentially reducing the number of drop structures required.

3.2.3.2 Side Slopes

The flatter the side slopes, the more stable are the banks. For grassed channels, channels with wetland bottoms, and bioengineered channels, side slopes should not be steeper than 4H:1V. Under special conditions in areas of existing development (i.e., not new development) and where right-of-way is a problem, the slopes may be as steep as 3H:1V; however, the designer is cautioned that operation of mowing equipment may not be safe on side slopes that are steeper than 4H:1V. Channels that require minimal slope maintenance such as concrete channels may have side slopes as steep as 1.5H:1V, although public safety issues must be taken into account. For riprap-lined channels, side slopes should not be steeper than 2.5H:1V.

For vegetated channels with underlying riprap, slopes must accommodate maintenance. For example, a grassed channel with underlying riprap should have side slopes no steeper than 4H:1V, as required for a grassed channel.

Local standards or conditions may require flatter side slopes. Side slopes steeper than 3H:1V are not recommended in residential areas or areas with frequent foot traffic. Fencing or railings may need to be considered if side slopes will be steeper than 3H:1V in these areas.

3.2.4 Curvature and Transitions

Generally, the gentler the 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 centerline curvature of the channel shall have a radius of at least twice the top width of the 100-year flow channel. The exception to this axiom is for concrete channels that may experience *supercritical* flow conditions. From a practical standpoint, it is generally not advisable to have any curvature in a channel conveying *supercritical* flow, since minor perturbations can be amplified as they move downstream.

Superelevation 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, and the depth of flow is also greater on the outside of a curve due to centrifugal force. This rise in water surface on the outside of a curve is referred to as superelevation. For *subcritical* flows, superelevation can be estimated by:

$$\Delta y = \frac{V^2 T}{2 g r_c} \qquad \text{(MD-9)}$$

in which:

Δy = increase in water surface elevation above average elevation due to superelevation (ft)

V = mean flow velocity (ft/sec)

T = top width of the channel under design flow conditions (ft)

g = gravitational constant = 32.2 ft/sec^2

r_c = radius of curvature (ft)

Transitions (expansions and contractions) are addressed in Section 4.4 (riprap-lined channels) and in Section 5.0 of the HYDRAULIC STRUCTURES chapter.

3.2.5 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 a number of specific channel types in Section 4.0 of this chapter; however, in general, a minimum residual freeboard of 1 to 2 feet should be allowed between the water surface and top of bank.

3.2.6 Erosion Control

Erosion control pertains to major drainage channels on the watershed scale as well as the drainage corridor scale. On the watershed scale, erosion and sediment control is critical in areas of urbanization, especially active construction areas, to prevent loading of initial and major drainageways with excessive sediment from disturbed areas in the watershed. Poor control of erosion on the watershed scale can result in increased maintenance and decreased capacity of major drainageways. Watershed erosion and sediment control is beyond the scope of this *Manual* but is regulated at the federal, state, regional, and local levels. In the State of Colorado, the Colorado Department of Public Health and Environment administers the National Pollutant Discharge Elimination System (NPDES) of the CWA, which requires stormwater management measures including erosion and sediment controls for construction sites larger than 1 acre under the Stormwater Permitting Regulations. In addition, most localities in Colorado require erosion and sediment control measures for construction sites.

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. While 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 changes. 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 Denver area, most waterways will need the construction of drops 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. The designer 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, such as riprap, may be 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 dryer can reduce the risk of erosion from storm runoff. Temporary stabilization measures including seeding and mulching and erosion controls such as installation and maintenance of silt fencing should be used during construction of major drainage improvements to minimize erosion.

3.2.7 Summary of Preliminary Design Guidance

Table MD-2 summarizes the guidance for the preliminary design of man-made channels discussed above. This guidance is for simple trapezoidal shapes to approximate alignment and geometry. Final design of man-made channels of a more complex nature will be discussed in Section 4.0.

Table MD-2—Trapezoidal Channel Design Guidance/Criteria

Design Item	Major Drainage Chapter Section	Criteria for Various Types of Channel Lining			
		Grass: Erosive Soils	Grass: Erosion Resistant Soils	Riprap	Concrete
Maximum 100-yr velocity	3.2.1	5.0 ft/sec	7.0 ft/sec	12.0 ft/sec	18.0 ft/sec
Minimum Manning's *n*—stability check	Table MD-3	0.03	0.03	0.03	0.011
Maximum Manning's *n*—capacity check	Table MD-3	0.035	0.035	0.04	0.013
Maximum Froude number	3.2.1	0.5	0.8	0.8	N/A
Maximum depth outside low-flow zone	3.2.2	5.0 ft	5.0 ft	n/a	N/A
Maximum channel longitudinal slope	3.2.3.1	0.6%	0.6%	1.0%	N/A
Maximum side slope	3.2.3.2	4H:1V	4H:1V	2.5H:1V	1.5H:1V [4]
Minimum centerline radius for a bend	3.2.4	2 x top width	2 x top width	2 x top width	2 x top width
Minimum freeboard [3]	3.2.5	1.0 ft [1]	1.0 ft [1]	2.0 ft [1]	2.0 ft [2]

[1] Suggested freeboard is 2.0 ft to the lowest adjacent habitable structure's lowest floor.

[2] For supercritical channels, use the freeboard recommended in Section 4.3.1.5 for final design.

[3] Add superelevation to the normal water surface to set freeboard at bends.

[4] Side slopes may be steeper if designed as a structurally reinforced wall to withstand soil and groundwater forces.

3.2.8 Maintenance Eligibility

The minimum design criteria requirements below must be satisfied as of June 2001 for a major drainage channel to be eligible for District maintenance assistance. Note that the District's *Maintenance Eligibility Guidelines* may change with time. The reader is directed to the District's Web site (www.UDFCD.org) for the latest version of the *Maintenance Elegibility Guidelines*.

3.2.8.1 Natural Channels (Open Floodplain Design)

When a developer chooses to stay out of the 100-year floodplain, the following requirements must be met:

1. If the total flow of the channel and floodplain is confined to an incised channel and erosion can be expected to endanger adjacent structures, 100-year check structures are required to control erosion and degradation of the channel area. See the HYDRAULIC STRUCTURES chapter of this *Manual* for more information. In addition, sufficient right-of-way shall be reserved to install the equivalent of a trapezoidal grass-lined channel that satisfies the velocity criteria specified in Table MD-2. Extra width shall be reserved where drop structures are needed, in which locations a 20-foot-wide maintenance access bench shall be provided along one side of the channel.

2. If the floodplain is wide and the low-flow channel represents a small portion of the floodplain area, low-flow check structures are usually required, unless it can be demonstrated that the channel will remain stable as the watershed urbanizes.

3. Consult the applicable Urban Drainage and Flood Control District's master plan document for guidance on the design event and stable steam or waterway longitudinal slope.

4. For either of the above cases, a maintenance access trail shall be provided. It should be designed according to the guidelines for grass-lined channels in Section 3.2.8.3, below.

3.2.8.2 Open Floodway Design (Natural Channel With Floodplain Encroachment)

Although floodplain preservation is preferable, when the design involves preserving the floodway while filling and building on the fringe area, the developer must meet the requirements in Section 3.2.8.1, and the fill slopes must be adequately protected against erosion with:

1. Fill slopes of 4H:1V or flatter that are vegetated according to the criteria in the REVEGETATION chapter.

2. Fill slopes protected by rock (not broken concrete or asphalt) riprap meeting District criteria with up to 2.5H:1V slopes.

3. Retaining walls, no taller than 3.5 feet, with adequate foundation protection.

3.2.8.3 Grass-Lined Channel Design

The design for a grass-lined channel must meet the following criteria to be eligible for District maintenance:

1. Side slopes should be 4H:1V or flatter.

2. Continuous maintenance access, such as with a trail, must be provided. The stabilized trail surface must be at least 8 feet wide with a clear width of 12 feet. It shall be located above the minor event water surface elevation (usually 2- to 10-year event, as directed by local government), but never less than 2-feet (3-feet for streams with perennial flow). Trail profiles need to be shown for all critical facilities such as roadway crossings, stream crossings and drop structures. All access trails shall connect to public streets. Maintenance trials need not be paved, but must be of all-weather construction such as aggregate base course, crusher fines, recycled concrete course or Aggregate Turf Reinforced Grass Pavement (RGP) described in Volume 3 of this *Manual* and capable of sustaining loads associated with large maintenance equipment. Paved trails are encouraged to allow for recreational use of the trails. When paved, pavement should be 5-inches minimum thickness of concrete (not asphalt). Maximum longitudinal slope for maintenance-only trails is 10%, but less than 5% when used as multi-purpose recreational trails to meet the requirements of the *Americans with Disabilities Act*. The District may accept adjacent public local streets or parking lots in lieu of a trail.
3. A low-flow or trickle channel is desirable. See Section 4.1.5 of this chapter for criteria.
4. Wetland bottom and bioengineered channels are acceptable when designed according to District wetland bottom channel criteria in Section 4.2 of this chapter.
5. The channel bottom minimum cross slope for dry bottom channels shall be 1%.
6. Tributary inflow points shall be protected all the way to the low-flow channel or trickle channel to prevent erosion. Inflow facilities to wetland bottom channels shall have their inverts at least 2 feet above the channel bottom to allow for the deposition of sediment and shall be protected with energy dissipaters.
7. All roadway crossings of wetland bottom channels shall incorporate a minimum of a stblized 2-foot drop from the outlet to the bottom of the downstream channel in order to preserve hydraulic capacity as sediment deposition occurs ovcer time in the channel.
8. All drop structures shall be designed in accordance with the HYDRAULIC STRUCTURES chapter of this *Manual*. Underdrain and storm sewer outlets located below the stilling basin’s end sills are not acceptable. Construction plans shall utilize District standard details.
9. Storm sewer outlets shall be designed in accordance with the criteria in Sections 5.0, 6.0, and 7.0 of this chapter. Alternatively, conduit outlet sstructures, including low tailwater riprap basins design described in Section 3.0 of the HYDRAULIC STRUCTURES chapter of the *Manual* shall be used when appropriate.
10. Grouted boulder rundowns and similar features shall be designed in accordance with Section 7.0

of the HYDRAULIC STRUCTURES chapter of the *Manual*.

11. Grass seeding specifications provided by the District (see the REVEGETATION chapter of this *Manual*) are recommended unless irrigated blue grass is used. The District will not maintain irrigated blue grass (due to cost constraints), but other elements of such a channel (i.e., drop structures, trickle channel) can still qualify for maintenance eligibility.

3.3 Choice of Channel Type and Alignment

3.3.1 Types of Channels for Major Drainageways

The types of major drainage channels available to the designer are almost infinite, depending only upon 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:

Natural Channels—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. Photograph MD-5 shows a natural channel serving as a major drainageway for an urbanized area.

Photograph MD-5—Natural channel (open floodplain design) serving as a major drainageway. Note the preservation of riparian vegetation, absence of floodplain encroachment and the use of grade control structures to arrest thalweg downcutting (i.e., channel incising/degradation)

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 should be stabilized with grade control structures to prevent downcutting, depression of the water table, and degradation of natural vegetation. Low-flow areas may need to be armored or otherwise stabilized to guard against erosion. Photograph MD-6 shows a grass-lined major drainage channel.

Photograph MD-6—Engineered grass-lined major drainageway with low-flow channel with bioengineered components integrated into the design.

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 should 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 biostabilization that includes rock lining to protect against undermining and bank erosion. Photograph MD-6 shows a composite channel.

Concrete-Lined Channels—Concrete-lined channels are high velocity artificial drainageways that are not recommended for use in urban areas. However, in retrofit situations where existing flooding problems need to be solved and where right-of-way is limited, concrete channels may offer advantages over other types of open drainageways. A concrete-lined channel is shown in Photograph MD-8.

Photograph MD-7—Composite channel.

Photograph MD-8—Concrete-lined channel.

Riprap-Lined Channels—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. Riprap may also be useful for bank line protection along sections of channels susceptible to erosion such as outer banks of bends. Photograph MD-9 shows a riprap-lined major drainage channel.

Photograph MD-9—Riprap channel. Burying and revegetation of the rock (i.e., soil riprap) could make this site blend into the adjacent terrain very nicely.

Bioengineered Channels—Bioengineered channels utilize vegetative components and other natural materials in combination with structural measures to stabilize existing channels in existing urban areas, area 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. Photographs MD-10 and 11 show examples of bioengineered major drainage channels. Wetland bottom channels are an example of one type of bioengineered channel.

Photograph MD-10—Bioengineered major drainage channel using low-grade control structure provides long-term structural integrity and diverse ecology.

Photograph MD-11—Bioengineered major drainageway with dense and diverse vegetation and energy dissipator.

Channels with Manufactured Liners—A variety of artificial channel liners are on the market, intended to protect the channel banks and bottom from erosion at higher velocities. These include gabions, interlocked concrete blocks, concrete revetment mats formed by injecting concrete into double layer fabric forms, and various types of synthetic fiber liners. All of these types are best considered for helping to solve existing urban flooding problems and are not recommended for new developments. Each type of channel lining has to be scrutinized for its merits, applicability, ability to meet other community needs, long term integrity, maintenance needs and maintenance costs.

Boatable Channels—Larger, natural, perennial waterways such as the South Platte River, Clear Creek, and Boulder Creek in the Denver metropolitan area are regularly used for boating and, because of their size and capacity, are subject to more comprehensive hydraulic analyses and considerations. Unless there is evidence of erosion, suitable natural armoring of the channel should not be disturbed; however, boater-friendly drop structures and diversion structures are often necessary. Refer to the discussion on boatable channels in the HYDRAULIC STRUCTURES chapter of this *Manual*.

3.3.2 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 pressure fluctuations
- Momentum transfer

Environmental Considerations

Neighborhood character

Neighborhood aesthetic requirements

Street and traffic patterns

Municipal 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

Prior to choosing the channel type, the planner should consult with experts in related fields in order to choose the channel that will create the greatest overall benefits. Whenever practical, the channel should have slow flow characteristics, be wide and shallow, and be natural in its appearance and functioning (Bohan 1970).

3.3.3 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 type of channel or drainageway improvements to be used, a flow chart is presented in Figure MD-4. The flow chart contains a series of questions to be considered in light of the requirements in this *Manual* and the requirements of the CWA, Section 404 (dredge and fill in jurisdictional wetlands and "Waters of the United States").

Following 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 can 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, investigate the stability of the natural drainageway and its banks, design measures to stabilize the longitudinal grade and banks, if needed, in selected areas, and obtain, if necessary, Section 404 permits and other approvals for these improvements. However, it is suggested that the reader review the latest Maintenance Eligibility Guidelines available at the District's Web site before deciding what improvements to natural channels are needed to qualify for the District's maintenance eligibility.

If the decision is to channelize, then determine whether the existing natural drainageway has a perennial flow, evidence of wetland vegetation, or is a well-established ephemeral 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 suggest that the designer check with the local USACE office early to determine which permit will be needed. Keep in mind that it is the responsibility of the proponent to comply with all applicable federal and state laws and regulations. Approvals by the local authorities do not supercede or waive compliance with these federal laws.

3.3.4 Maintenance

All major drainage channels in urban areas will require maintenance to ensure that they are capable of conveying their design flow, such as the 100-year flow (as well as more frequently occurring flows) and to ensure that channels do not become a public nuisance and eyesore. Routine maintenance (i.e., mowing for weed control or annual or seasonal clean-outs), unscheduled maintenance (i.e., inspection and clean-out after large events) and restorative maintenance after some years of operation should be expected.

Native tall grasses may require mowing three to six times a year or on a less frequent schedule, depending on the type of channel and setting. Mowing cuts down the presence of "standing dead" grasses and place them on the ground where decomposition can take place. Often mowing of dry-land native grasses during the growing season may not be necessary, except for weed control.

A maintenance access platform 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 platform is needed. The local government may require the road to be surfaced with 6-inches of Class 2 road base or a 5-inch-thick concrete slab.

Channels may be eligible for District maintenance assistance if they are designed and constructed in accordance with the criteria in this *Manual*, are under some form of public ownership, and meet the District Maintenance Eligibility Guidelines that are stated in Section 3.2.8 of this chapter (see District Web site for periodic updates).

3.4 Design Flows

The major drainage system, including 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. Methods for calculating this flow are described in the RAINFALL and RUNOFF chapters of this *Manual*. In addition to consideration of the 100-year event, the designer must also consider events of lesser magnitudes. For the low-flow channel, ⅓ to ½ of the 2-year flow for fully developed conditions, assuming no upstream detention, is recommended for 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.

3.5 Choice of Channel Lining

Where the project requires a waterway for storm runoff to be lined because of either hydraulic, topographic, or right-of-way needs, there are a number of choices for linings including grass and other types of vegetation (see the REVEGETATION chapter), other natural materials, riprap, concrete, and manufactured lining materials. The major criterion for choosing a lining is that the lining selected must be designed to withstand the various forces and actions that tend to overtop the bank, damage the lining, and erode unlined areas.

Natural-like channel linings are encouraged; however, in some situations where right-of-way is limited within the constraints of an already-urbanized area, hard-lined channels (i.e., riprap or concrete) may be necessary to assure a stable drainageway. Hard-lined channels are most applicable in solving existing urban flooding problems and are not recommended for new developments.

Natural-like channel linings need to have gentle to mild slopes and are especially desirable for residential areas and areas with public access.

Manufactured channel linings such as gabions, interlocked concrete blocks, synthetic linings, etc., are not recommended for new developments. As with concrete- and riprap-lined channels, all of these types are best considered for helping to solve existing urban flooding problems where right-of-way is very limited. Manufactured channel linings should be used with caution, and each type of channel lining must be scrutinized for its merits, applicability, ability to meet other community needs, long term integrity, and maintenance needs and costs.

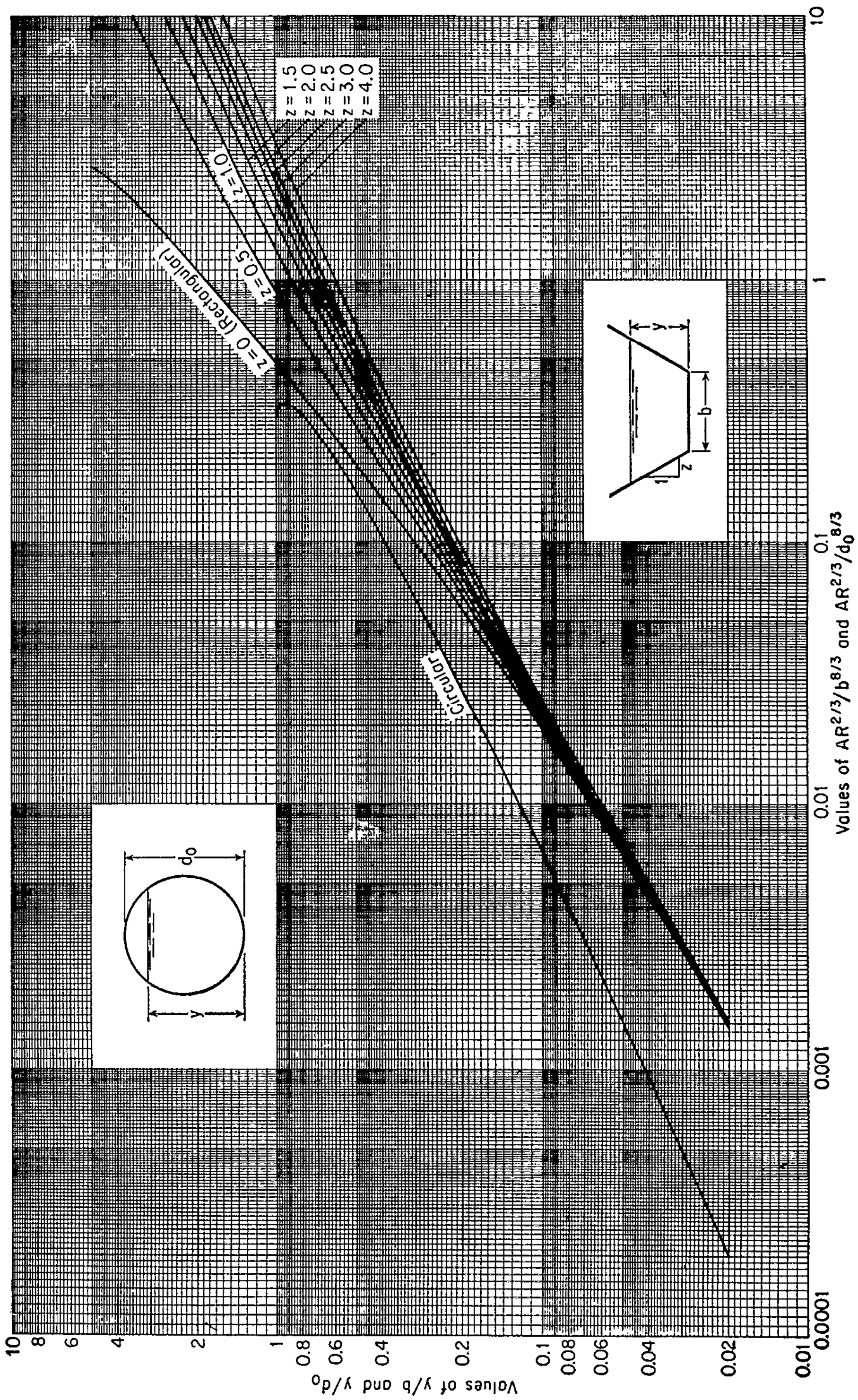


Figure MD-2—Normal Depth for Uniform Flow in Open Channels

(Fletcher and Grace 1972)

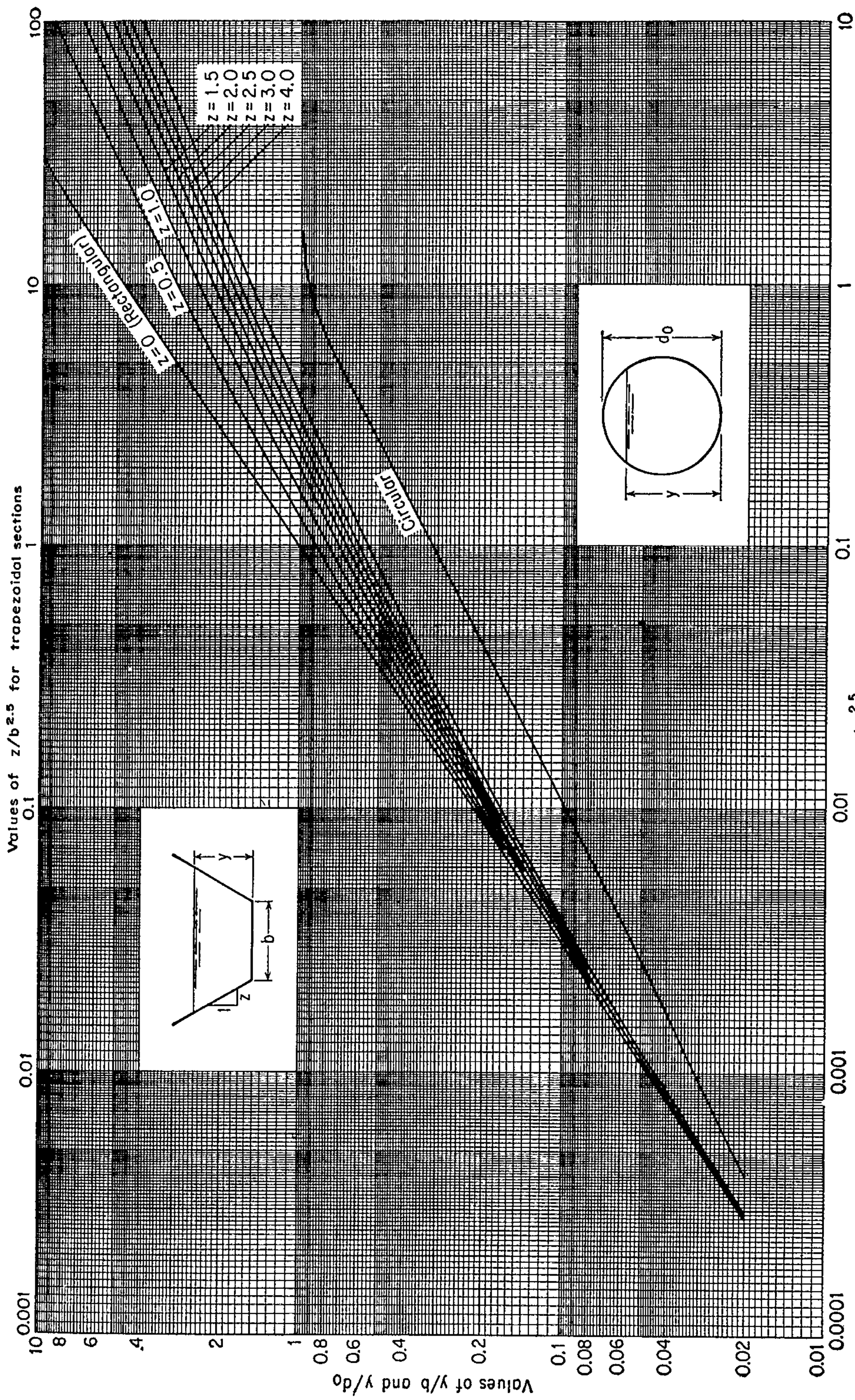


Figure MD-3—Curves for Determining the Critical Depth in Open Channels

(Fletcher and Grace 1972)

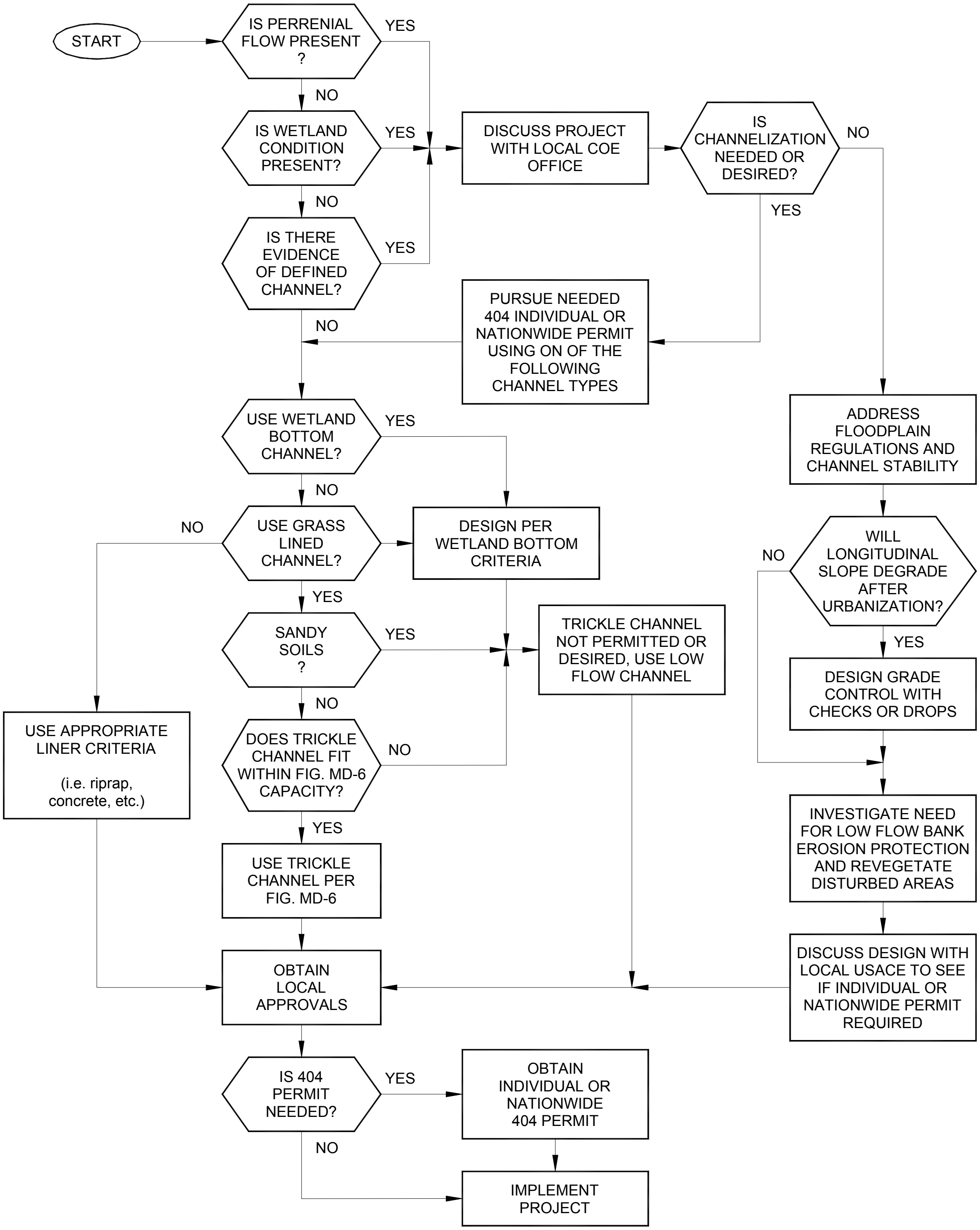


Figure MD-4—Flow Chart for Selecting Channel Type and Assessing Need for 404 Permit

4.0 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 3.0 can be applied using these design criteria to determine channel geometry and hydraulics.

4.1 Grass-Lined Channels

Grass-lined channels may be considered the most desirable type of artificial channels for new development where natural channels are absent or have limited environmental value. Channel storage, lower velocities, and wildlife, aesthetic, and recreational benefits create significant advantages over other types of channels. The design must fully consider aesthetics, sediment deposition, scouring, hydraulics, safety, and maintenance. Photograph MD-6 shows a grass-lined channel.

4.1.1 Design Criteria

These design criteria are particularly useful in preliminary design and layout work. Any final design that has parameters that vary significantly from those described below should be carefully reviewed for adequacy. Figures MD-5, MD-7, and MD-8 provide representative sketches for grass-lined channels.

4.1.1.1 Design Velocity and Froude number

In determining flow velocity during the major design storm (i.e., 100-year) 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 recommended maximum normal depth velocities and Froude numbers for 100-year flows are listed in Table MD-2.

4.1.1.2 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 flow is occurring. As preliminary criteria, the design depth of flow for the major storm runoff flow should not exceed 5.0 feet in areas of the channel cross section outside the low-flow or trickle channel area.

4.1.1.3 Design Slopes

To function without instability, grass-lined channels normally have longitudinal slopes ranging from 0.2 to 0.6%. Where the natural slope is steeper than desirable, drop structures should be utilized.

With respect to side slopes, the flatter the side slope, the more stable it is. For grassed channels, side slopes should not be steeper than 4H:1V. Under special conditions where development exists and right-of-way is a problem, the slopes may be as steep as 3H:1V; however, the designer is cautioned that operation of mowing equipment may not be safe on side slopes that are steeper than 4H:1V.

4.1.1.4 Curvature

The more gentle the curve, the better the channel will function. At a minimum, centerline curves shall have a radius that is greater than two times the top width (i.e., $2 \cdot T$) of the 100-year design flow (or other major flow) in the channel.

4.1.1.5 Design Discharge Freeboard

Bridge deck bottoms and sanitary sewers often control the freeboard along the channel in urban areas. Where such constraints do not control the freeboard, the allowance for freeboard should 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 1 to 2 feet should be allowed between the water surface and top of bank. Along major streams such as the South Platte River, Clear Creek, Boulder Creek, and others where potential for much timber and other debris exists during a flood, a 3-foot freeboard is recommended.

For curves in the channel, superelevation should be evaluated using Equation MD-9 in Section 3.2.4 and should be included in addition to freeboard.

4.1.2 Grass and Vegetation Selection and Use

Please refer to the REVEGETATION chapter.

4.1.3 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 MD-5.

4.1.3.1 Side Slopes

The flatter the side slopes, the better. Side slopes should not be steeper than specified in Section 4.1.1.3 of this chapter.

4.1.3.2 Depth

The maximum depth should not exceed the guidelines in Section 4.1.1.2 of this chapter. For known channel geometry and discharge, normal water depth can be calculated using Manning's Equation from Section 3.1.1 of this chapter.

4.1.3.3 Bottom Width

The bottom width should 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 using the depth, velocity, and Froude number constraints in Sections 4.1.1.1 and 4.1.1.2 using Manning's Equation from Section 3.1.1 of this chapter.

4.1.3.4 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. A trickle channel with a porous bottom (i.e., unlined or riprapped) 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, especially for larger major drainageways, streams and rivers, or for channels located on sandy soils. Criteria for low-flow/trickle channels are presented in Section 4.1.5 of this chapter.

4.1.3.5 Outfalls Into Channel

Outfalls into grass-lined, major channels should be at least 1 foot (preferably 2 feet) above the channel invert with adequate erosion protection provided.

4.1.4 Roughness Coefficients

The hydraulic roughness of man-made grass-lined channels depends on the length of cutting (if any), the type of grass, and the depth of flow (Steven, Simons, and Lewis 1971). Table MD-1 summarizes typical roughness coefficients for grass-lined channels, and Table MD-2 provides guidance for the coefficients for simple trapezoidal channels.

4.1.5 Trickle and Low-Flow Channels

The low flows, and sometimes 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 because of lawn irrigation return flow and other sources, both overland and from groundwater inflow. Continuous flow over grass or what used to be ephemeral 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.

These new perennial flows in previously ephemeral waterways change the composition of vegetation. However, it may be possible to plant species adapted to the new hydrologic regime. More mesic species could be planted as flows increase to establish a better-adapted native vegetation type. In some cases, namely in man-made channels, a concrete-lined trickle channel may guard against erosion; however, low-flow/trickle channels with natural-like linings are more attractive visually. Low-flow channels shall be used for larger major drainageways, streams, and rivers and for channels located on sandy soils. Trickle channels with natural-like linings offer and advantage over concrete-lined trickle channels because they more closely mimic natural channels, have greater aesthetic appeal, and provide habitat benefits and vegetative diversity. These linings are best when porous and allow exchange of water with adjacent groundwater table and sub-irrigate 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. Low-flow channels with natural-like linings must be carefully designed to guard against erosion.

Low flows must be carried in a trickle channel, a low-flow channel, or an underdrain pipe. The capacity of a trickle channel should be approximately 2.0% of the major (i.e., 100-year) design flow for the fully developed condition assuming no upstream detention. If an underdrain pipe is used, it should be at least 24 inches in diameter, have access manholes at least every 200 feet, and have a slope so that a velocity of at least 3 ft/sec is maintained at ½ full pipe depth. Underdrains are subject to sediment deposition and are very expensive to maintain. As a result, the District does not recommend, nor will consider them for maintenance eligibility.

Figure MD-6 should be used to estimate the required capacity of a trickle flow channel based on the percent of impervious area, I_a. For flows exceeding the limits in Figure MD-6 or where a natural gulch or stream exists, a separate low-flow channel having stabilized banks should be used. A low-flow channel should have a minimum capacity of ⅓ to ½ of the 2-year peak flow under the fully developed watershed conditions. To the extent practicable, a low-flow channel should be gently sloped and shallow to promote flow through the channel's vegetation. See Figure MD-7 and MD-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 should be mixed prior to placement for these low-flow channels. Soil-riprap low-flow channels should have a cross slope of 1% to 2% (they may be "dished out"). It's longitudinal slope should be consistent with the channel type used.

4.1.6 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 erosion-control measures and corrective steps will be needed after a major runoff event. The use of drops and checks 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.

Under bridges, grass will not grow; therefore, the erosion tendency is larger. A cut-off wall at the downstream edge of a bridge is a good practice.

4.1.6.1 Erosion at Bends

Often special erosion control measures are often needed at bends, (see Section 4.1.1.4). An estimate of protection and velocity along the outside of the bend needs to be made using the following guidelines:
When $r_c/T \geq 8.0$, no riprap 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 riprap sized per Section 4.4.2.3 using an adjusted channel velocity determined using Equation MD-10.

$$V_a = (-0.147\,\frac{r_c}{T} + 2.176)\,V \qquad \text{(MD-10)}$$

in which:

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

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

r_c = channel centerline radius

T = Top width of water during the major design flood

Riprap should be applied to the outside ¼ of the channel bottom and to the channel side slope for the entire length of the bend plus a distance of $2 \cdot T$ downstream of the bend. 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.

Construction of channels, should be accomplished in a manner that retards erosion of bare soil areas. Downstream streams, channels, culverts and storm sewers experience severe silting problems if erosion is not controlled during construction by use of contour furrows and aggressive mulching during and after construction. In addition, to control erosion from construction site runoff all concentrated flows have be intercepted and conveyed across or around the construction site in a pipe or a lined open channel. Consult Volume 3 of this *Manual* for detailed guidance on erosion control.

4.1.6.2 Riprap Lining of Grass-lined Channels

For long-term maintenance needs, it is recommended 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 recommended (i.e., 4H:1V), with certain exceptions in retrofit situations in older urbanized areas with limited right of way, where a maximum steepness of 3H:1V may be used.

4.1.7 Water Surface Profile

Water surface profiles should be computed for all channels, typically for the 10-year and 100-year events. Computation of the water surface profile should include standard backwater methods, taking into consideration all losses due to changes in velocity, drops, bridge openings, and other obstructions. Computations should begin at a known point and extend in an upstream direction for subcritical flow. It is for this reason that the channel should be designed from a downstream direction to an upstream direction. It is necessary to show the hydraulic and energy grade lines on all preliminary drawings to help ensure against errors. Whether or not the energy grade line is shown on the final drawings is an option of the reviewing agency, although the District encourages this.

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.

4.1.8 Maintenance

Grass-lined channels must be designed with maintainability in mind. See Section 3.2.8 for the District's Maintenance Eligibility Guidelines, which also provide guidance for elements of design that permit good maintenance of these installations. A stable maintenance access road with a minimum passage width of 12 feet shall be provided along the entire length of all major drainageways. The local government may require the road to have an all weather surface such as a 5-inch-thick concrete pavement.

4.1.9 Calculation Tool

Calculations for sizing of a grass-lined channel using hydraulic equations from Section 3.0 and criteria from Section 4.1 can be performed using the **Grass Ch Worksheet** of the UD-Channels Spreadsheet. The **Composite Design Worksheet** of the UD-Channels Spreadsheet can be used for the design of a grass-lined channel with a low-flow channel. An example of this tool is provided in Example MD-2, which is located at the end of this chapter.

4.1.10 Design Submittal Checklist

Table MD-3 provides a design submittal checklist for a grass-lined channel.

Table MD-3—Design Submittal Checklist for Grass-Lined Channel

Criterion Requirements	✓
Maximum velocity for 100-year event: ≤ 5.0 ft/sec for erosive soils ≤ 7.0 ft/sec for erosion-resistant soils	
Manning's *n* ≥ 0.035 used to check capacity Froude Number	
Manning's *n* ≤ 0.030 used to check velocity and maximum Froude Number	
Froude number: < 0.5 for erosive soils and < 0.8 for non-erosive soils	
Maximum depth for 100-year event ≤ 5.0 ft outside of trickle channel	
Longitudinal channel slope ≥0.2% and ≤ 0.6%	
Side slopes no steeper than 4H:1V	
Channel bottom cross-slope 1% to 2%	
Centerline curve radius > 2 x top width for 100-year event	
Channel bends checked for needed erosion protection (see Section 4.1.6.1 Erosion Control" of the Major Drainage Chapter).	
Channel bend protection, use Type V or VL soil riprap lining extended below channel bottom, buried and vegetated when called for at bends (see Section 4.1.6.1).	
Outfalls into channel ≥ 1 foot above channel invert (use pipes, concrete-lined rundowns or grouted boulder rundowns)	
Adequate freeboard provided, including superelevation	
Grass species appropriate (drought resistant, sturdy, easily established, turf forming)	
Trickle channel (if any) sized for 2.0% of 100-year design flow for fully developed, undetained condition in u/s watershed.	
Underdrain pipe (if any) diameter ≥ 24 inches [**Note: not recommended or endorsed**.]	
Underdrain pipe (if any) includes manhole access every 200 ft	
Underdrain pipe (if any) velocity ≥ 3.0 ft/sec when one-half full	
Erosion protection measures included where necessary	
District Maintenance Eligibility Guidelines satisfied	
Continuous maintenance access road provided (minimum 8-foot stable surface with 12-foot clear width, 20-feet at drop structures)	
Energy and hydraulic grade lines calculated, plotted, design discharges annotated	

4.2 Composite Channels

When the trickle flow channel capacity limits are exceeded as discussed earlier, the use of a composite channel is required, namely a channel with a stabilized low-flow section and an overflow section above it to carry major flow. It is best to assume that wetland and other flow-retarding vegetation will develop in the los-flow section over time. A fact that needs to be accounted for when designing a composite channel. 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 (see Photograph MD-7 for representative example). In other cases, a composite channel with a wetland bottom low-flow channel may better suit individual site 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 channel 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. In developed areas, where right-of-way is limited, mitigating flood damages should take precedence over other considerations during project design. In cases where existing wetlands are eliminated or otherwise impacted, off-site wetland mitigation may be required by the USACE's 404 Permit.

4.2.1 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, affects the channel roughness, and the rate of sediment deposition on the bottom. These assumptions are based on state-of-the-art literature, observed sediment loads in stormwater (USEPA 1983, DRCOG 1983) and locally observed sediment buildup (District 1996) in several existing wetland bottom and composite channels in the Denver area.

The recommended criteria parallel the criteria for the design of grass-lined channels (Section 4.1), 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, these types of 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. 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 ⅓ to ½ of the 2-year peak required for low-flow channels. Figures MD-8 illustrates a representative wetland bottom composite channel. The use on an appropriate Manning's *n* in its design is critical and guidance for one can be found in Figure MD-9. More detailed design guidance for wetland bottom channels may be found in Volume 3 of this *Manual*.

In designing low-flow 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 should be at least 2 feet above the low-flow channel invert. Guidance for the design of a wetland bottom channel for water quality purposes is given in the STRUCTURAL BMPs chapter in Volume 3 of this *Manual*. A typical cross-sections for composite channels is shown in Figure MD-7.

4.2.2 Design Procedure

If a wetland bottom channel is to be used, the designer may utilize the *CWC Worksheet* from the *Design Forms Spreadsheet* provided for Volume 3 of this *Manual* to assist in these calculations. Otherwise use the *Open Channel Design* workbook. Both may be downloaded from the www.udfcd.org web site.

After the low-flow channel has been designed, complete the design by providing additional channel capacity for the major flows in accordance with the grass-lined channel design requirement. The final Manning's *n* for the composite channel shall be determined using Equation MD-11.

$$n_c = \frac{P \cdot R^{5/3}}{\dfrac{P_L \cdot R_L^{5/3}}{n_L} + \dfrac{P_M \cdot R_M^{5/3}}{n_M} + \dfrac{P_R \cdot R_R^{5/3}}{n_R}} \qquad \text{(MD-11)}$$

In which:

n_c = Manning's n for the composite channel

n_L = Manning's n for the left overbank

n_R = Manning's n for the right overbank

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

P_L = Wetted perimeter of the left overbank

P_R = Wetted perimeter of the right overbank

P_M = Wetted perimeter of the middle area

R_L = Hydraulic radius of the left overbank

R_R = Hydraulic radius of the right overbank

R_M = Hydraulic radius of the middle area

Figure MD-9 is provided to assist the designer in determining Manning's n for the low-flow section of a composite channel when the design water depth is known.

Whenever a composite bottom channel is crossed by a road, railroad, or a trail requiring a culvert or a bridge, a drop structure should 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 recommended (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 MD-10).

Water surface profiles must be computed, typically for the 10- and 100-year events. Computation of the water surface profile should 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 for this reason that the channel should be designed from a downstream direction to an upstream direction. It is necessary to show the energy gradient on all preliminary drawings to help prevent errors. Whether or not the energy gradient line is shown on the final drawings is the option of the reviewing agency but is encouraged by the District.

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.

Guidance regarding vegetation selection, planting, and maintenance is provided in the REVEGETATION chapter.

4.2.3 Life Expectancy and Maintenance

The low-flow channel can serve as a productive ecosystem and can also be highly effective at trapping sediment. Wetland vegetation bottom channels are expected to fill with sediment over time. Some sediment accumulation is necessary for a wetland 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 should 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.

A maintenance access road with a minimum passage width of 12 feet shall be provided along the entire length of all major drainageways. The local government may require the road to be surfaced with 6 inches of Class 2 roadbase or a 5-inch-thick concrete slab.

4.2.4 Calculation Example for Wetland Bottom Channel

See Volume 3 of this *Manual* for a design example.

4.2.5 Design Submittal Checklist

Table MD-4, below, provides a design checklist for a composite channel.

Table MD-4—Design Submittal Checklist for Composite Channel

Criterion/Requirement	✓
Maximum velocity in main channel outside of the low-flow or wetland low-flow section for the 100-year event: ≤ 5.0 ft/sec for erosive soils ≤ 7.0 ft/sec for non-erosive soils	
"New channel" roughness condition used to set longitudinal slope	
"Mature channel" roughness condition used to evaluate capacity	
Composite Manning's n calculated for channel and used in hydraulic computations	
Froude number: < 0.5 for erosive soils; < 0.8 for non-erosive soils	
Maximum depth for 100-year event ≤ 5.0 ft outside of low-flow channel	
Side slopes in low-flow section, no steeper than 2.5H:1V for soil riprap lined (i.e., rock mixed with topsoil, covered with topsoil and revegetated)	
Side slopes above low-flow channel: no steeper than 4H:1V	
Centerline curve radius: > 2 x top width for 100-year event	
Channel bends: check for need for erosion protection in accordance with recommendation of section "4.1.6.1 Erosion at Bends" of the *USDCM*	
Channel bend protection, use Type V or VL soil riprap lining extended below channel or low-flow channel bottom, buried and vegetated if called for at bends (see Section 4.1.6.1).	
Outfalls into channel: ≥ 1 foot above channel invert (use pipes, concrete-lined rundowns or grouted boulder rundowns)	
Adequate freeboard provided, including superelevation	
Vegetation Species appropriate for anticipated hydroperiod, water levels, zonation on banks (see the REVEGETATION chapter)	
No impermeable lining present	
Drop downstream of each culvert or bridge crossing: 1-foot to 2-foot for wetland bottom channels	
Low-flow channel size: ⅓ to ½ of the 2-year flow for the fully developed watershed flows	
Low-flow channel depth: ≥ 3.0 ft and ≤ 5.0 ft	
Erosion protection measures included where necessary (at crossing, drops, bend, etc.)	
District Maintenance Eligibility Guidelines satisfied	
Continuous maintenance access road provided (minimum 8-foot stable surface with 12-foot clear width, 20-foot at drop structures)	
Energy and hydraulic grade lines calculated and plotted (min. 2- and 100-year flows)	

4.3 Concrete-Lined Channels

Although not recommended for general use because of safety and structural integrity and aesthetic reasons; hydraulic, topographic, or right-of-way constraints may necessitate the use of a concrete-lined channel in some instances. 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 will typically not be eligible for District's maintenance eligibility.

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 are preferred for subcritical flows. The use of a concrete-lined channel for subcritical flows should not be used except in unusual circumstances where a narrow right-of-way exists. Vegetated channels are normally preferable in the Denver region because available thalweg slopes are generally steep enough.

Channels conveying supercritical flows must be carefully designed due to many potential hazards. Imperfections at joints can cause their rapid deterioration, in which case a complete failure of the channel can occur. In addition, high-velocity flow at cracks or joints creates an uplift force by creating zones of flow separation with negative pressures and conversion of the velocity head to pressure head under the liner, which can virtually tear out concrete slabs. When designing a lined channel with supercritical flow, the designer must use utmost care and consider all relevant factors.

In the Denver region, all channels carrying supercritical flow shall be lined with continuously reinforced concrete linings, both longitudinally and laterally. There shall be no diminution of wetted area cross sections at bridges or culverts. Adequate freeboard shall be provided to have a suitable safety margin. Bridges or other structures crossing the channel must be anchored satisfactorily to withstand the full dynamic load that might be imposed upon the structure in the event of major trash plugging.

The concrete linings must be protected from hydrostatic uplift forces, which are often created by a high water table or momentary inflow behind the lining from localized flooding. A perforated underdrain pipe is required under the lining, and the underdrain must be designed to be free draining. At supercritical flow, minor downstream obstructions do not create any backwater effect. Backwater computation methods are applicable for computing the water surface profile or the energy gradient in channels having a supercritical flow; however, the computations must proceed in a downstream direction.

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 ensure that the particular roughness is obtained. Because of field construction limitations, the designer should use a Manning's n roughness coefficient equal to 0.013 for a well-trowelled concrete finish. Other finishes should have proportionately larger n values assigned to them. A value of n higher than 0.013 may be applicable for a concrete channel with subcritical flow if deposition of sediment or transport of sediment as bedload is expected.

Small concrete channels that function as rundowns are addressed in the HYDRAULIC STRUCTURES chapter.

4.3.1 Design Criteria

4.3.1.1 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 at *Froude Numbers* between 0.7 and 1.4 are unstable and unpredictable and should 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 should utilize Manning's Equation from Section 3.1.1 of this chapter with roughness values from Table MD-5. 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 MD-5—Roughness Values for Concrete-Lined Channels

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

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

4.3.1.2 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.

4.3.1.3 Curvature

Curvature is not allowed for channels with supercritical flow regimes. For concrete-lined channels with subcritical flow regimes, the centerline radius of curvature should be at least two times the top width, and superelevation should be evaluated for all bends using Equation MD-9 in Section 3.2.4 and included in determining freeboard.

4.3.1.4 Design Discharge Freeboard

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

$$H_{fb} = 2.0 + 0.025V(y_0)^{1/3} + \Delta y \quad \text{(MD-12)}$$

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 superelevation at bends (see Equation MD-9) (no bends allowed in supercritical channels)

In addition to H_{fb}, add height of estimated standing waves, superelevation and/or other water surface disturbances to calculate the total freeboard. In all cases, the freeboard shall be no less than 2 feet and the concrete lining shall be extended above the flow depth to provide the required freeboard.

4.3.2 Concrete Lining Specifications

4.3.2.1 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 7 inches for supercritical channels and no less than 5 inches for subcritical channels. A free draining granular bedding shall be provided under the concrete liner and shall be no less than 6-inches thick for channels with Froude number ≤ 0.7 and 9-inches thick for channels with Froude number ≥ 1.4.

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. In addition, fencing along concrete channels should be used to restrict access for safety reasons.

4.3.2.2 Concrete Joints

Concrete joints must satisfy the following criteria:

1. Channels shall be constructed of continuously reinforced concrete without transverse joints.

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.

3. Longitudinal joints, where required, shall be constructed on the sidewalls at least 1 foot vertically

above the channel invert.

4. All joints shall be designed to prevent differential movement.

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

4.3.2.3 Concrete Finish

The surface of the concrete lining may be finished in any of the finishes listed in Table MD-5, provided appropriate finishing technique is used. Check with local authorities to determine which finishes are acceptable.

4.3.2.4 Underdrain

Longitudinal underdrains shall be provided along the channel bottom on 10-foot centers within a free-draining bedding under the channel lining, be free draining, and daylight at check drops (when applicable). A check valve or flap valve shall be provided at the outlet to prevent backflow into the drain. Appropriate numbers of weep holes and one-way valves shall be provided in vertical wall sections of the channel to relieve hydrostatic pressure.

4.3.3 Channel Cross Section

4.3.3.1 Side Slopes

The side slopes shall be no steeper than 1.5H:1V unless designed to act as a structurally reinforced wall to withstand soil and groundwater forces.

4.3.3.2 Depth

Maximum depth shall be consistent with Section 4.3.1.2. For known channel geometry and discharge, normal water depth can be calculated using Manning's Equation recommended in Section 3.1.1.

4.3.3.3 Bottom Width

The bottom width should 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 Sections 4.3.1.1, 4.3.1.2, and 4.3.1.3 using Manning's Equation.

4.3.3.4 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.

4.3.3.5 Outfalls Into Channel

Outfalls into concrete-lined channels should be at least 1 foot above the channel invert.

4.3.4 Safety Requirements

A 6-foot-high chain-link or comparable fence shall be installed to prevent access wherever the 100-year channel concrete section depth exceeds 3 feet. Appropriate numbers of gates, with top latch, 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.

4.3.5 Calculation Tools

Calculations for sizing of a concrete-lined channel using hydraulic equations from Section 3.0 and criteria from Section 4.3 can be performed using the *Basis Worksheet* of UD-Channels Spreadsheet.

4.3.6 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. A maintenance access road with a minimum passage width of 12 feet shall be provided along the entire length of all major drainageways. The local government may require the road to have an all weather surface such as 5-inch-thick concrete pavement.

4.3.7 Design Submittal Checklist

Table MD-6 provides a design checklist for a concrete-lined channel.

Table MD-6—Design Submittal Checklist for Concrete-Lined Channel

Criterion/Requirement	✓
Maximum velocity for 100-year event ≤ 18 ft/sec	
Channel capacity and Froude Number ≥ 1.4: checked with Manning's n = 0.013	
Maximum velocity and Froude Number ≤ 0.7: checked using Manning's n = 0.011	
Froude number ≤ 0.7 and ≥ 1.4 under both Manning's n assumptions	
Side slopes no steeper than 1.5H:1V	
Centerline curve radius for subcritical channels: > 2 x top width for 100-year event	
Centerline curve radius for supercritical channels: NO CURVATURES PERMITTED	
Concrete lining designed to withstand hydrodynamic and hydrostatic forces (minimum thickness = 7.0 inches for supercritical channels, 5.0 inches for subcritical channels)	
Concrete joints meet Section 4.3.2.2 criteria	
Free draining granular bedding under concrete (6-inch minimum thickness for Fr ≤ 0.7, 9-inch minimum thickness for Fr ≥ 1.4	
Free draining longitudinal underdrains provided on 10-ft centers, including check or flap valve at outlet to prevent backflow	
Concrete finish from list in Table MD-5	
Outfalls into channel ≥ 1 ft above channel invert	
Adequate freeboard provided (see criteria in text)	
Standing waves included in freeboard for supercritical channels	
6-ft chain link fence (or comparable) provided when channel depth > 3.0 ft	
Ladder-type steps spaced no more than 200 ft apart on alternating sides of channel with lowest rung approximately 12 inches above channel invert	
District Maintenance Eligibility Guidelines satisfied	
Continuous maintenance access road provided (minimum 8-foot stable surface with 12-foot clear width, 20-foot at drops)	
Energy and hydraulic grade lines calculated and plotted for the channel and also annotate the design discharges	

4.4 Riprap-Lined Channels

Channel linings constructed from soil riprap, grouted boulders, or wire-encased rock to control channel erosion may be considered on a case-by-case basis, or may be required as the case may be, 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 (5 ft/sec for sandy soil conditions and 7 ft/sec in erosion resistant soils) 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 transition s.

Design criteria applicable to these situations are presented in this section. Riprap-lined channels should only be used for subcritical flow conditions where the Froude number is 0.8 or less. When used, it is recommended that all riprap outside frequent flow zones have the voids filled with soil, the top of the rock covered with topsoil, and the surface revegetated with native grasses, namely, use soil riprap.

4.4.1 Types of Riprap

4.4.1.1 Ordinary and Soil Riprap

Ordinary riprap, or simply "riprap," refers to a protective blanket of large loose stones, which are usually placed by machine to achieve a desired configuration. The term ordinary riprap has been introduced to differentiate loose stones from grouted boulders and wire-enclosed rock. Photograph MD-9 shows a representative riprap-lined channel, while Figures MD-11 through MD-14 depict key design aspects of such channels.

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 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 for the riprap, which allows leaching of channel particles through the riprap blanket.

Classification and gradation for riprap and boulders are given in Table MD-7, Table MD-8 and Figure MD-11 and are based on a minimum specific gravity of 2.50 for the rock. Because of its relatively small size and weight, riprap types VL, L and M must be mixed with native topsoil, covered with topsoil and revegetated. This practice also protects the rock from vandalism.

The type of riprap that is mixed with native soil as described above is called *soil riprap*. Soil Riprap consist of 35% by volume of native soil, taken from the banks of the channel, that is mixed in with 65% by volume of riprap on-site, before placement as channel liner. Soil riprap is recommended for all urban channels within District regardless of riprap size used. A typical section for soil riprap installation is illustrated in Figure MD-13b.

Table MD-7—Classification and Gradation of Ordinary Riprap

Riprap Designation	% Smaller Than Given Size by Weight	Intermediate Rock Dimensions (inches)	d_{50} (inches)*
Type VL	70-100	12	
	50-70	9	
	35-50	6	6**
	2-10	2	
Type L	70-100	15	
	50-70	12	
	35-50	9	9**
	2-10	3	
Type M	70-100	21	
	50-70	18	
	35-50	12	12**
	2-10	4	
Type H	70-100	30	
	50-70	24	
	35-50	18	18
	2-10	6	
Type VH	70-100	42	
	50-70	33	
	35-50	24	24
	2-10	9	

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

** Mix VL, L and M riprap with 35% topsoil (by volume) and bury it with 4 to 6 inches of topsoil, all vibration compacted, and revegetate.

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 should be less than one-third its length, and rounded stone should be avoided.
- The rock should sustain a loss of not more than 40% after 500 revolutions in an abrasion test (Los Angeles machine—ASTM C-535-69) and should 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 should rock have a specific gravity less than 2.50.

4.4.1.2 Grouted Boulders

Table MD-8 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 ordinary 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 recommended that grouted boulders on channel banks and outside of frequent flow areas be buried with topsoil and revegetated with native grasses, with or without shrubs depending on the local setting. Boulders used for grouting should meet all the properties of rock for ordinary riprap, and rock of uniform size should be used. The boulder sizes are categorized in Table MD-8.

Table MD-8—Classification of Boulders

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

Grouted boulders should be placed directly on subbase without granular bedding. The top one-half of the boulders shall be left ungrouted and exposed. Weep holes should be provided at the toe of channel slopes and channel drops to reduce uplift forces on the grouted channel lining. Underdrains should be provided if water is expected to be present beneath the liner. Grouted boulders on the banks should be buried and vegetated with dry-land grasses and shrubs. Cover grouted boulders with slightly compacted topsoil, filling depressions and covering the top of the tallest rocks to a height of no less than 4-inches (6-inches of more preferred) to establish dry-land vegetation. Recommended grass seed mixtures and how to plant and much them are provided in the REVEGETATION chapter of this *Manual*. Shrubs also may be planted, but will not grow well over grouted boulders unless irrigated.

Two types of grout are recommended for filling the voids for the grouted boulders. The technical specifications for two types of structural grout mix are given as a part of Figures HS-7a4 and HS-7b4 of the HYDRAULIC STRUCTURES chapter of this *Manual*. 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 one-half 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 one-half of the boulders being used and keep the upper one-half ungrouted and clean. Remove all grout splatters off the exposed boulder portion immediately after grout injection using wet brooms and brushes.

4.4.1.3 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 or gravel will reduce the service life of the wire dramatically. Water that rolls or otherwise moves cobbles and large stones breaks 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. Wire-enclosed rock installations have been found to attract vandalism, and flat mattress surfaces seem to be particularly susceptible to having wires cut and stones removed. For these reasons, the District discourages the use of wire-enclosed rock. If the designer chooses to utilize gabions, they should be placed above the low-flow channel or 2-year water surface elevation. All flat mattresses must be filled with topsoil and then covered with a 6-inch layer of topsoil.

4.4.2 Design Criteria

The following sections present design criteria for riprap-lined channels. Additional information on riprap can be found in Section 7.0 of this chapter.

4.4.2.1 Design Velocity

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

4.4.2.2 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 2-year flood water surface, placed on a stable foundation.

4.4.2.3 Riprap Sizing

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

$$\frac{VS^{0.17}}{d_{50}^{0.5}(G_s - 1)^{0.66}} = 4.5 \qquad \text{(MD-13)}$$

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 MD-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 rundowns is provided in Section 7.0 of the HYDRAULIC STRUCTURES chapter of this *Manual*, and protection downstream of culverts is discussed in Section 7.0 of this chapter, as well as in the HYDRAULIC STRUCTURES chapter, Section 3.0.

Table MD-10 shall be used to determine the minimum size of rock type required. Note that rock types for ordinary riprap, including gradation, are presented in Table MD-7 and Figure MD-11.

Table MD-10—Riprap Requirements for Channel Linings[*]

$\dfrac{VS^{0.17}}{(G_s-1)^{0.66}}$ **	Rock Type
< 3.3	VL** (d_{50} = 6 inches)
≥ 3.3 to < 4.0	L** (d_{50} = 9 inches)
≥ 4.0 to < 4.6	M (d_{50} = 12 inches)
≥ 4.6 to < 5.6	H (d_{50} = 18 inches)
≥ 5.6 to 6.4	VH (d_{50} = 24 inches)

[*] Applicable only for a Froude number of < 0.8 and side slopes no steeper than 2H:1V.

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

Table MD-10 indicates that rock size does not need to be increased for steeper channel side slopes, provided the side slopes are no steeper than 2.5H:1V (District 1982). Rock-lined side slopes steeper than 2.5H:1V are considered 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 should be at least 1.75 times d_{50} (at least 2.0 times d_{50} in sandy soils) and should 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 should be increased 50% for at least 3 feet to prevent undercutting.

4.4.2.4 Riprap Toes

Where only the channel sides are to be lined and the channel bottom remains unlined, additional riprap is needed to protect such lining. In this case, the riprap blanket should extend at least 3 feet below the channel thalweg (invert) in erosion resistant soils, and the thickness of the blanket below the existing channel bed should be increased to at least 3 times d_{50} to accommodate possible channel scour during higher flows. The designer should compute the scour depth for the 100-year flow and, if this scour depth exceeds 3 feet, the depth of the riprap blanket should be increased accordingly (see Figure MD-12). As an alternative, a thinner layer of riprap (i.e., 1.75 to 2.0 d_{50}) may be used in the toe provided it is extended to 5.0 feet below the channel bottom. For sandy soils, it will be necessary to extend the riprap toe to even greater depths (5-foot minimum) and site-specific scour calculations are recommended.

4.4.2.5 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; riprap is commonly used for this. The need for protection of the bank on the outside of the bend has been discussed in Section 4.1.6 for channel bends that have a radius less than 8 times the top width of the channel cross section.

Whenever an outside bend in a grass-lined channel needs protection, soil riprap should be used, then covered with native topsoil and revegetated to provide a grassed-line channel appearance. Note that buried soil riprap may lose its cover in a major event if vegetation has not fully matured, requiring re-burial and revegetation.

The minimum allowable radius for a riprap-lined bend is 2.0 times the top width of the design flow water surface. The riprap protection should be placed along the outside of the bank and should be extended downstream from the bend a distance of not less than 2.0 times the top width of the channel. The riprap does not need to be extended upstream of the point of curvature (start of the bend).

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 MD-10. Use the adjusted velocity in Table MD-10 to select appropriate riprap size.

4.4.2.6 Transitions

Scour potential is amplified by turbulent eddies near rapid changes in channel geometry such as transitions and bridges. Table MD-10 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 should 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.

4.4.2.7 Design Discharge Freeboard

Freeboard above the design water surface shall not be less than that determined by Equation MD-12 in Section 4.3.1.5.

In addition to the freeboard height calculated using Equation MD-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.

4.4.3 Roughness Coefficient

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

$$n = 0.0395 d_{50}^{1/6} \quad \text{(MD-14)}$$

In which, d_{50} = the mean stone size in feet.

This equation does not apply to grouted boulders or to very shallow flow (where hydraulic radius is less than, or equal to 2.0 times the maximum rock size). In those cases the roughness coefficient will be greater than indicated by Equation MD-14.

4.4.4 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 in common use: (1) a granular bedding filter and (2) filter fabric.

4.4.4.1 Granular Bedding

Two methods for establishing gradation requirements for granular bedding are described in this section. The first method, a single or two-layer bedding that uses Type I and II gradations, is shown in Table MD-11 and is adequate for most ordinary riprap and grouted riprap applications. The second utilizes a design procedure developed by Terzaghi, which is referred to as the T-V (Terzaghi-Vicksburg) design (Posey 1960, USACE 1970). The T-V filter criteria establish an optimum bedding gradation for a specific channel soil. The latter requires channel soil information, including a gradation curve, while the Type I and Type II bedding specifications given in Table MD-11 and Figure MD-13 are applicable whether or not soil information is available.

Table MD-11—Gradation for Granular Bedding

U.S. Standard Sieve Size	Percent Weight by Passing Square-Mesh Sieves	
	Type I CDOT Sect. 703.01	Type II CDOT Sect. 703.09 Class A
3 inches	-----	90-100
1½ inches	-----	-----
¾ inches	-----	20-90
⅜ inches	100	-----
#4	95-100	0-20
#16	45-80	-----
#50	10-30	-----
#100	2-10	-----
#200	0-2	0-3

The Type I and Type II bedding specifications shown in Table MD-11 were developed using the T-V filter criteria and the fact that bedding which will protect an underlying non-cohesive soil with a mean grain size of 0.045 mm will protect anything finer. Since the T-V filter criterion provides some latitude in establishing bedding gradations, it is possible to make the Type I and Type II bedding specifications conform with Colorado Division of Highways' aggregate specifications. The Type I bedding in Table MD-11 is designed to be the lower layer in a two-layer filter for protecting fine-grained soils and has a gradation identical to Colorado Department of Transportation's (CDOT's) concrete sand specification AASHTO M-6 (CDOT Section 703.01). Type II bedding, the upper layer in a two-layer filter, is equivalent to Colorado Division of Highways' Class A filter material (Section 703.09 Class A) except that it permits a slightly larger maximum rock fraction. When the channel is excavated 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 MD-12. At drop structures, a combination of filter fabric and Type II bedding is acceptable as an alternative to a two-layer filter.

Table MD-12—Thickness Requirements for Granular Bedding

Riprap Designation	Minimum Bedding Thickness (inches)		
	Fine-Grained Soils*		Coarse-Grained Soils**
	Type I	Type II	Type II
VL (d_{50} = 6 in), *L* (d_{50} = 9 in)	4	4	6
M (d_{50} = 12 in)	4	4	6
H (d_{50} = 18 in)	4	6	8
VH (d_{50} = 24 in)	4	6	8

* May substitute one 12-inch layer of Type II bedding. The substitution of one layer of Type II bedding 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.

The specifications for the T-V reverse filter relate the gradation of the protective layer (filter) to that of the bed material (base) by the following inequalities:

$$D_{15(filter)} \leq 5d_{85(base)} \quad \text{(MD-15)}$$

$$4d_{15(base)} \leq D_{15(filter)} \leq 20d_{15(base)} \quad \text{(MD-16)}$$

$$D_{50(filter)} \leq 25d_{50(base)} \quad \text{(MD-17)}$$

in which, the capital "D" and lower case "d" refer to the filter and base grain sizes, respectively. The subscripts refer to the percent by weight, which is finer than the grain size denoted by either D or d. For example, 15% of the filter material is finer than $D_{15(filter)}$ and 85% of the base material is finer than $d_{85(base)}$. Application of the T-V filter criteria is best described using an example provided in Section 4.4.8.

4.4.4.2 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 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. This prevents free drainage, increasing 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 MD-14 for details on acceptable use of filter fabric as bedding.

4.4.5 Channel Cross Section

4.4.5.1 Side Slopes

For long-term maintenance needs, it is recommended 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-line channels is recommended (i.e., 4H:1V), with certain exceptions in retrofit situations with limited right of way, where a maximum steepness of 3H:1V may be used.

Riprap-lined and soil riprap-lined side slopes when used as described above that are 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 may be considered.

4.4.5.2 Depth

The maximum depth should be consistent with the guidelines in Section 4.4.2.2 of this chapter. For known channel geometry and discharge, normal water depth can be calculated using Manning's Equation from Section 3.1.1 of this chapter.

4.4.5.3 Bottom Width

The bottom width should 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 Sections 4.4.2.1, 4.4.2.2, and 4.4.2.3 using Manning's Equation from Section 3.1.1 of this chapter.

4.4.5.4 Outfalls Into Channel

Outfalls into riprap-lined channels should be at least 1 foot (preferably 2 feet) above the channel invert.

4.4.6 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 with erosion is control of erosion in the watershed tributary to the channel. Good erosion control practices in the watershed will reduce channel maintenance. In addition, accumulation of debris in the channel, especially after a large event, may be of concern due to the potential for movement of riprap and damming.

4.4.7 Maintenance

A maintenance access road with a minimum passage width of 12 feet shall be provided along the entire length of all major drainageways. The local government may require the road to have an all weather surface such as 5-inch-thick concrete pavement. Requirements for District maintenance eligibility are reviewed in Section 3.2.8 of this chapter. Of particular concern is the long-term loss of riprap, particularly due to the public removing rock. If grouted rock is used, follow the criteria for grouted boulders (i.e., use of grouted riprap is not an acceptable practice). Grout can deteriorate with time, and this should be monitored, as well. Improper grout installation creates long-term maintenance problems.

4.4.8 Calculation Example

Calculations for sizing a riprap-lined channel using hydraulic equations from Section 3.0 and criteria from Section 4.4 are shown in Example MD-3 using the **Riprap Worksheet** of the UD-Channels Spreadsheet. This example is located at the end of this chapter.

4.4.9 Design Submittal Checklist

Table MD-13 provides a design checklist for a riprap-lined channel.

Table MD-13—Design Submittal Checklist for Riprap-Line d Channel

Criterion Requirement	✓
Maximum normal depth velocity for 100-year event ≤12 ft/sec	
Channel capacity checked with Manning's n = 0.041	
Maximum velocity checked using Manning's n = 0.030	
Froude number ≤ 0.8	
Side slopes in low-flow channel and for toe protection in natural channel: no steeper than 2.5H:1V (see section 4.4.5.1).	
Use of soil riprap, buried with topsoil and revegetated, if type VL, L or M riprap in grass-lined channel is used. (Use of soil riprap is suggested for larger stones as well)	
Rock specific gravity ≥ 2.50 and meets other requirements in Section 4.1.1.1	
Riprap size determined using Equation MD-13 and Table MD-10	
Riprap blanket thickness ≥ 2.0 x d_{50}	
Blanket thickness increased at least 50% for ≥ 3 ft at upstream & downstream ends of lining	
Toe protection provided in accordance with Section 4.4.2.4	
Scour depth calculated for 100-yr flow to assure adequate toe thickness	
Outfalls into channel 1 to 2 ft above channel invert	
Riprap lined bend curve radius of the channel's centerline ≥ 2.0 x top width for 100-year event	
Channel bends size riprap using adjusted velocity in accordance with recommendations in section "4.1.6 Erosion Control" of the *USDCM*	
Riprap protection for outer bank of bend extended downstream at least 2 x 100-yr top width	
Minimum of 2.0 ft freeboard, including superelevation, for adjacent structures	
Riprap at transitions extended upstream by 5 ft and downstream by 5 x design flow depth	
Riprap sized for transitions using 1.25 times maximum transition velocity	
Appropriate gradation of granular bedding material per Section 4.4.4.1	
Adequate thickness for granular bedding Section 4.4.4.1	
District Maintenance Eligibility Guidelines satisfied	
Continuous maintenance access road provided (8-foot surface with 12-foot clear width, 20-foot at drop structures)	
Energy and hydraulic grade lines calculated and plotted for channel, with annotated design discharges shown	

4.5 Bioengineered Channels

Bioengineered channels (see Photographs MD-10 and MD-11) emphasize the use of vegetative components in combination with structural measures to stabilize and protect stream banks from erosion. The District advocates the integration of bioengineering techniques into drainage planning, design, and construction when the use of such channels is consistent with the District'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 4.2, Wetland Bottom Channels, and Section 4.6, Natural Channels; designers are encouraged to read Sections 4.2, 4.5 and 4.6, concurrently. In addition, because bioengineered channels require some structural assistance to maintain stability in urban settings, the designer is referred to guidance on drop structures in the HYDRAULIC STRUCTURES chapter.

4.5.1 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 should 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. Brush layering
4. Fiber rolls
5. Fascines
6. Live willow stakes (with and without joint plantings in soil filled rock)
7. Live plantings in conjunction with geotextile mats
8. Wide ranges of planting of wetland and upland vegetation

9. Wrapped soil lifts for slope stability

See Photographs MD-10 and MD-13 and Figures MD-15 through MD-18 for more guidance.

Photograph MD-12—Willow plantings and vegetation along bioengineered channel.

Photograph MD-13—Integration of open water areas with major drainageways provides habitat and aesthetic benefits in addition to providing storage.

4.5.2 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.

4.5.3 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 District. There are many sources of information on bioengineering that the designer should consult for additional information when planning and designing a bioengineered channel (Watson, Biedenharn, and Scott 1999; USFISRWG 1998; Riley 1998; and Biedenharn, Elliot, and Watson 1997).

4.5.4 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, especially in the semi-arid climate of the Denver area, purely 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 cannel toes and at outer channel banks (see Figures MD-16, MD-17 and MD-18).

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 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 of the hardened low-flow channel to the other, thereby establishing their own pattern.

Figure MD-19 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 should be placed on a Type L riprap foundation, and boulders should 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.

4.5.5 Advantages of Bioengineered Channels

Public reaction to bioengineered channels is generally favorable, not only in metropolitan Denver, but also regionally and nationally. 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 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.

4.5.6 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. The semi-arid conditions that characterize Denver can be at odds with the need for an adequate water supply for maintaining the vegetation. Careful species selection that reflects the site's soils and water availability characteristics is essential.
3. A basic design criterion within the District is to demonstrate channel stability during the major (100-year) storm, due to public safety and property protection concerns within urban areas. There is little evidence (locally, regionally, or nationally) as to whether purely 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 revegetation and bioengineering. Invasion by other species is quite likely over the years the bioengineered channel is in operation.

4.5.7 Design Guidelines

To provide the designer with guidelines for the applicability of bioengineered channels, a comparison of hydraulic characteristics is provided in Table MD-14 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 should be 1 to 2 feet above the channel invert.

Table MD-14—Guidelines for Use of Various Types of Channels

(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)	**
$F_{r5\text{-}year}$	0.4 (0.3)	0.6 (0.4)	0.7 (0.5)	**
$F_{r100\text{-}year}$	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, F_r, are based on site-specific design calculations.

4.6 Natural Channels

Natural waterways in the Denver region are sometimes in the form of steep-banked gulches, which have 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 bioengineering techniques, described in Section 4.5 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 Denver 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. In the Denver area, this slope, depending on watershed size and channel soils, has been observed to range from 0.2 to 0.6%, with the South Platte River itself approaching a slope of 0.1%. Whenever feasible, natural channels should 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, generally, 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 1.5.3 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 analyses, keep in mind that 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 STORAGE chapter of this *Manual*.

The following design criteria are recommended when evaluating natural channels:

1. The channel and overbank floodplain should have adequate capacity for the 100-year flood.
2. A water surface profile should be defined in order to identify the 100-year floodplain, to control

earthwork, and to build structures in a manner consistent with the District's and local 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 MD-1.
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 MD-1.
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 should 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.

4.7 Retrofitting Open-Channel Drainageways

Many projects involving major drainage system design will occur in areas that have already been developed, rather than in newly urbanizing areas. Design of major drainageways in these areas can be challenging due to limitations of the existing major drainage system, right-of-way constraints, community desires, and public acceptance. While underground conduits or hard-lined channels may be required in some situations, the designer should first consider the option of retrofitting a channel to provide flood conveyance and other recreational, aesthetic, environmental, and/or water quality benefits. Retrofitting a major drainage channel may be appropriate when:

1. The retrofitted channel will be capable of conveying the major flow event in a stable manner.
2. The retrofitted channel will provide recreational, aesthetic, environmental, and/or water quality benefits that other design options (i.e., an underground conduit or concrete channel) would not provide.
3. The retrofitted channel will not pose an increased public health or safety risk and, preferably, will be a safer alternative than other design options.

4.7.1 Opportunities for Retrofitting

Opportunities for retrofitting exist in many projects occurring in areas that have already been developed. Retrofitting is well suited to areas such as urban parks and designated open space areas where right-of-way is not too restricted by existing development. Retrofitting is especially favorable for redevelopment projects in urban areas that seek to incorporate the major drainageway as a feature of the development, providing aesthetic, recreational, and/or water quality benefits.

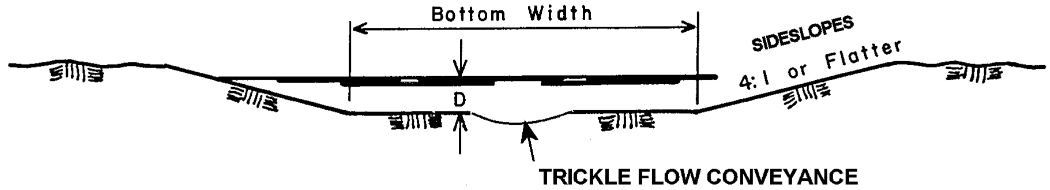
4.7.2 Objectives of Retrofitting

The foremost objective of retrofitting a drainageway must be to provide stable conveyance of the major flow event for the future developed condition of the watershed. Other objectives of retrofitting include:

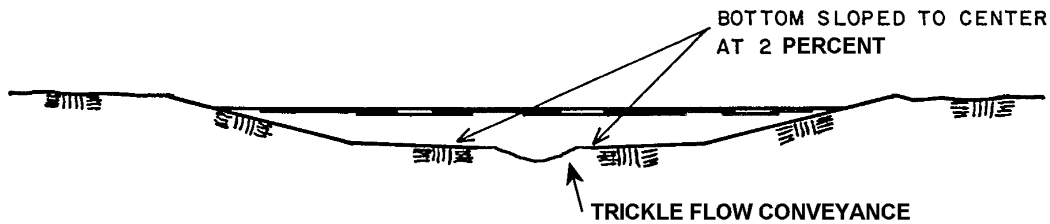
1. Creating multi-use areas. Uses that may be compatible with a well-designed retrofitted major drainageway include recreation, open space, parks and trails, wildlife corridors, restoration of vegetation for diversity and habitat, and others.
2. Enhancing channel aesthetics. Revegetation and landscaping can provide a riparian corridor that is attractive to the public as well as wildlife.
3. Enhancing water quality. Improved channel stabilization resulting from a major drainage channel retrofit has a direct benefit to water quality in reducing erosion and sediment transport. In addition, retrofitting can create aquatic habitat, and riparian vegetation and soil microorganisms can provide a degree of water quality treatment. Retrofitting can also be designed to limit access to some portions of the channel or to encourage access in specific areas that are more frequently maintained and/or equipped with trash cans.
4. Increasing benefit-to-cost ratio. For retrofitting to be acceptable, in most cases, it must be cost effective. Retrofitting an open channel may often be less expensive than constructing an underground conduit. Even when retrofitting costs are comparable to or higher than the costs of other design options, the multi-use potential for a retrofitted channel may justify the additional cost by providing benefits that otherwise would require separate facilities for each use.

4.7.3 Natural and Natural-Like Channel Creation and Restoration

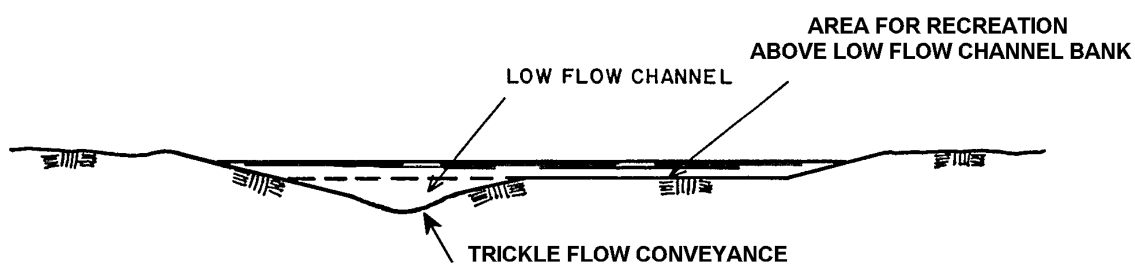
The designer should refer to Sections 4.1, 4.2, and 4.5 for guidance and criteria for creation of grass-lined channels, channels with wetland bottoms, and bioengineered channels, respectively.



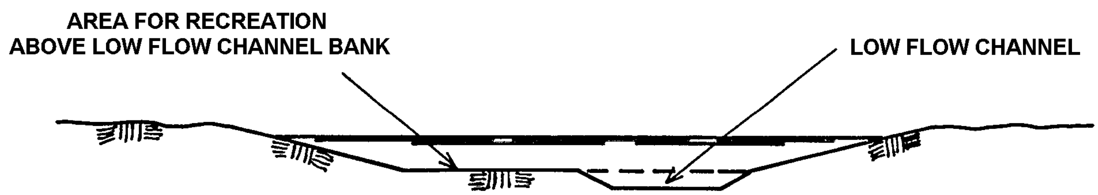
CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL



CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL

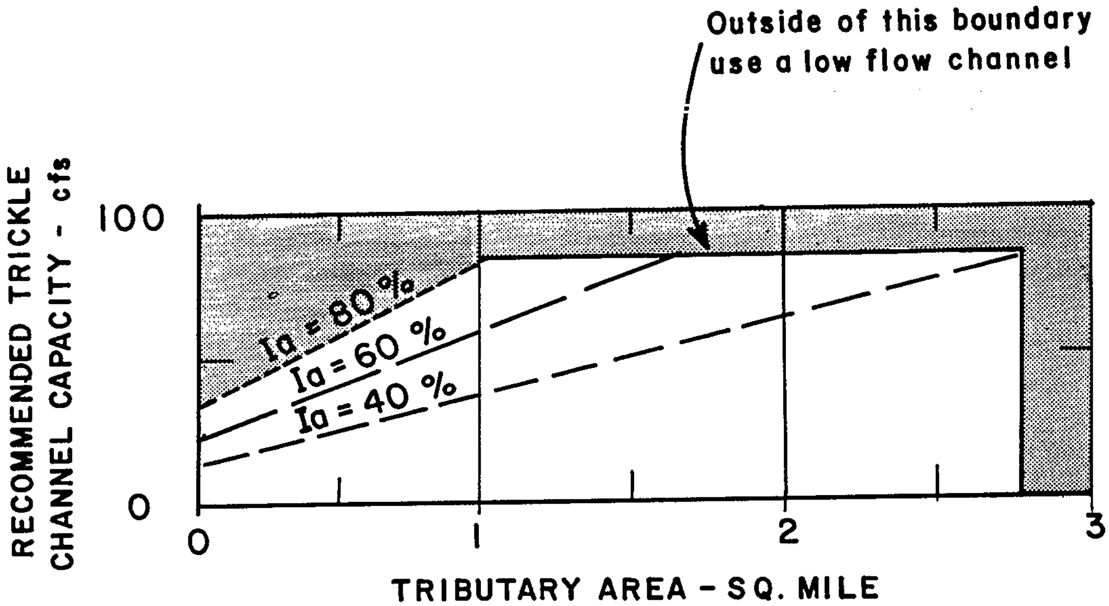


CROSS SECTION WITH LOW FLOW CHANNEL WITH TRICKLE CHANNEL
AREA FOR MAJOR DRAINAGE RUNOFF



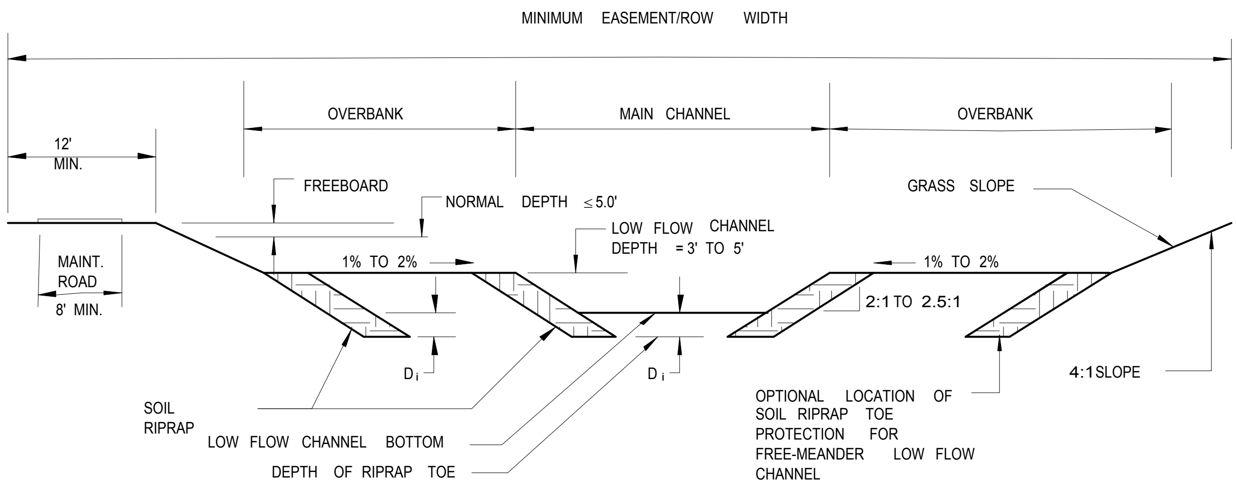
CROSS SECTION WITH LOW FLOW CHANNEL WITH
OVERFLOW AREA FOR MAJOR DRAINGAE RUNOFF

Figure MD-5—Typical Grassed Channels



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

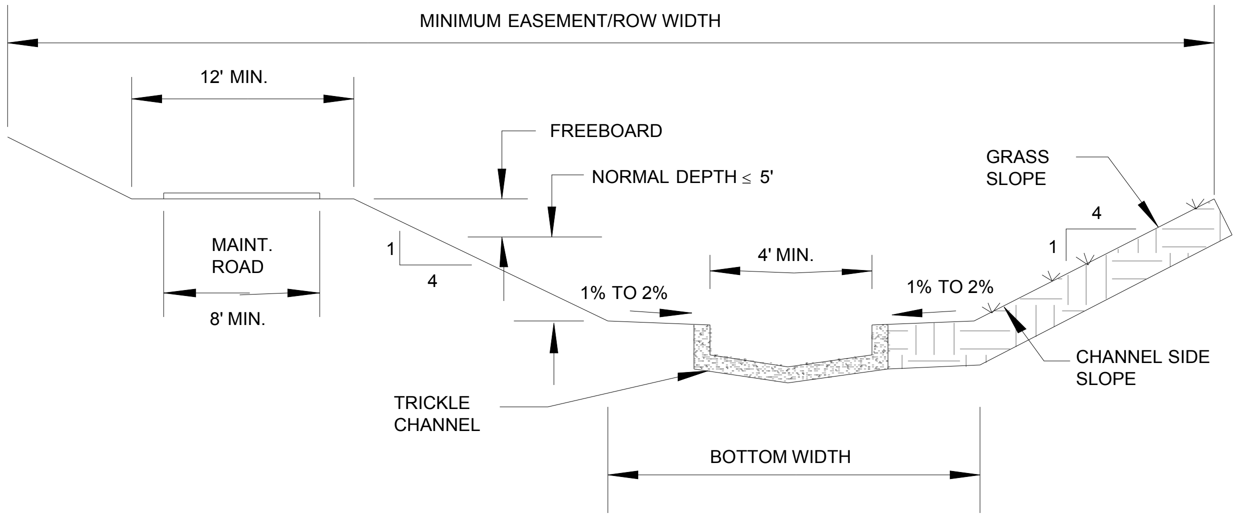
Figure MD-6—Minimum Capacity Requirements for Trickle Channels



NOTE:

1. LOW FLOW CHANNEL: CAPACITY TO BE THE EQUIVALENT OF $\frac{1}{3}$ TO $\frac{1}{2}$ OF THE 2-YEAR FLOW 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 7 FT/S FOR CHANNELS WITH EROSION RESISTANT SOILS OR 5 FT/S FOR CHANNELS WITH EROSIVE SOILS.
3. FREEBOARD: FREEBOARD TO BE A MINIMUM OF 1 FOOT.
4. MAINTENANCE ACCESS ROAD: MINIMUM STABLE WIDTH TO BE 8 FEET WITH A CLEAR WIDTH OF 12 FEET.
5. ROW 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 = 3-FOOT MINIMUM FOR EROSION RESISTANT SOILS.
   D_i = 5-FOOT MINIMUM FOR SANDY SOILS
8. CHANNEL SIDESLOPE ABOVE LOW-FLOW CHANNEL 4H:1V OR FLATTER, EVEN IF LINED WITH SOIL RIPRAP.
9. FROUDE NUMBER FOR ALL FLOWS SHALL NOT EXCEED 0.8 FOR EROSION RESISTANT SOILS AND 0.5 FOR EROSIVE SOILS.
10. THE CHANNEL CAN BE DESIGNED TO HAVE THE LOW-FLOW SECTION TO HAVE A WETLAND BOTTOM.

Figure MD-7—Composite Grass-line Channel with a Low-Flow Channel, including a Wetland Bottom Low-Flow Channel



NOTES:

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% OF 100-YEAR FLOW FOR THE FULLY DEVELOPED, UNDETAINED 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 7 FT/S FOR CHANNELS WITH EROSION RESISTANT SOILS OR 5 FT/S FOR CHANNELS WITH EROSIVE SOILS.

4. FREEBOARD: FREEBOARD TO BY A MINIMUM OF 1 FOOT.

5. MAINTENANCE ACCESS ROAD: MINIMUM STABLE WIDTH TO BE 8 FEET WITH CLEAR WIDTH OF 12 FEET.

6. EASEMENT/ROW 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 4:1.

8. FROUDE NUMBER: MAXIMUM VALUE FOR MINOR AND MAJOR FLOODS SHALL NOT EXCEED 0.8 FOR CHANNELS WITH EROSION RESISTANT SOILS OR 0.5 FOR CHANNELS WITH EROSIVE SOILS.

Figure MD-8—Grass-lined Channel with a Trickle Channel

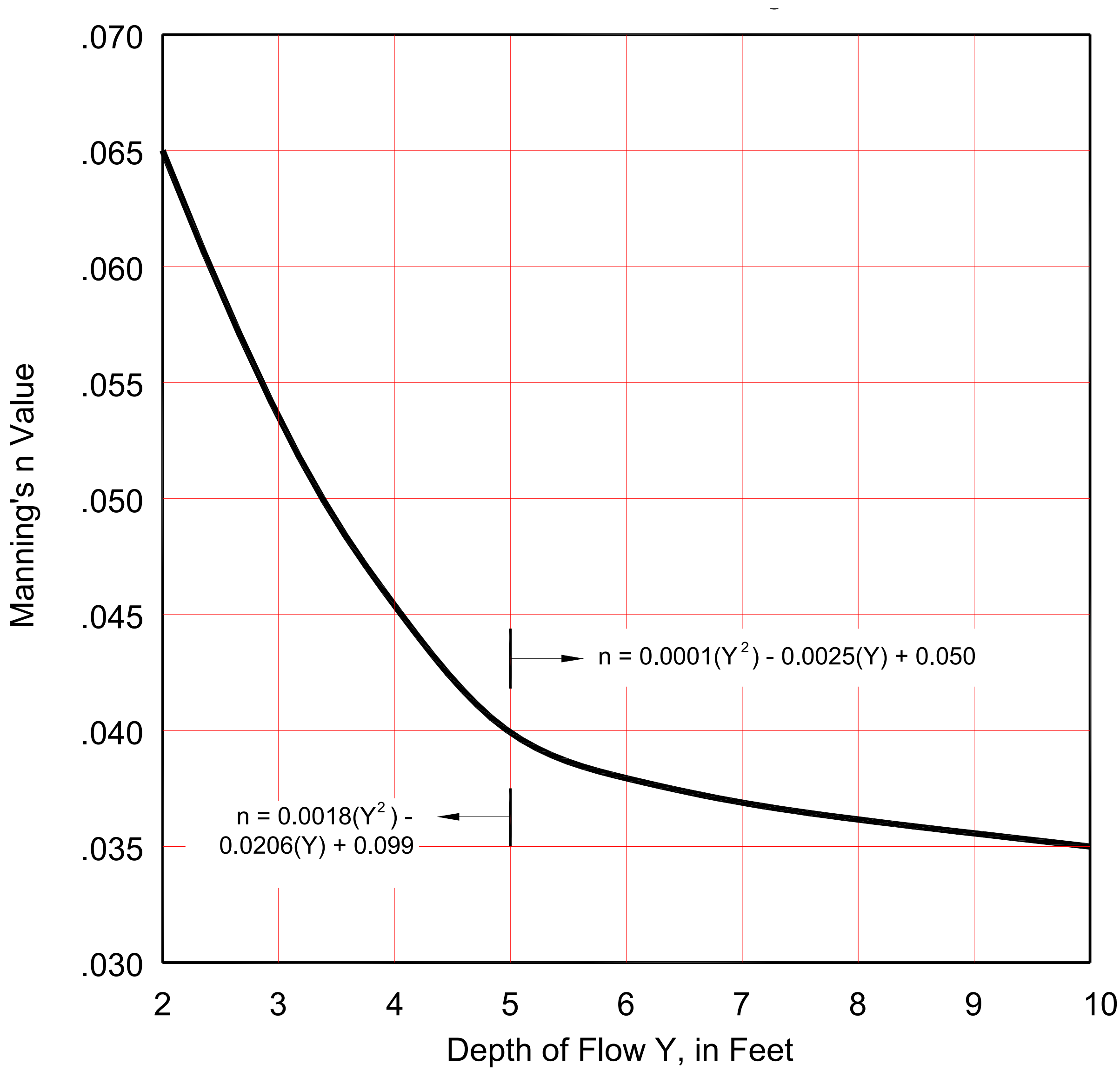
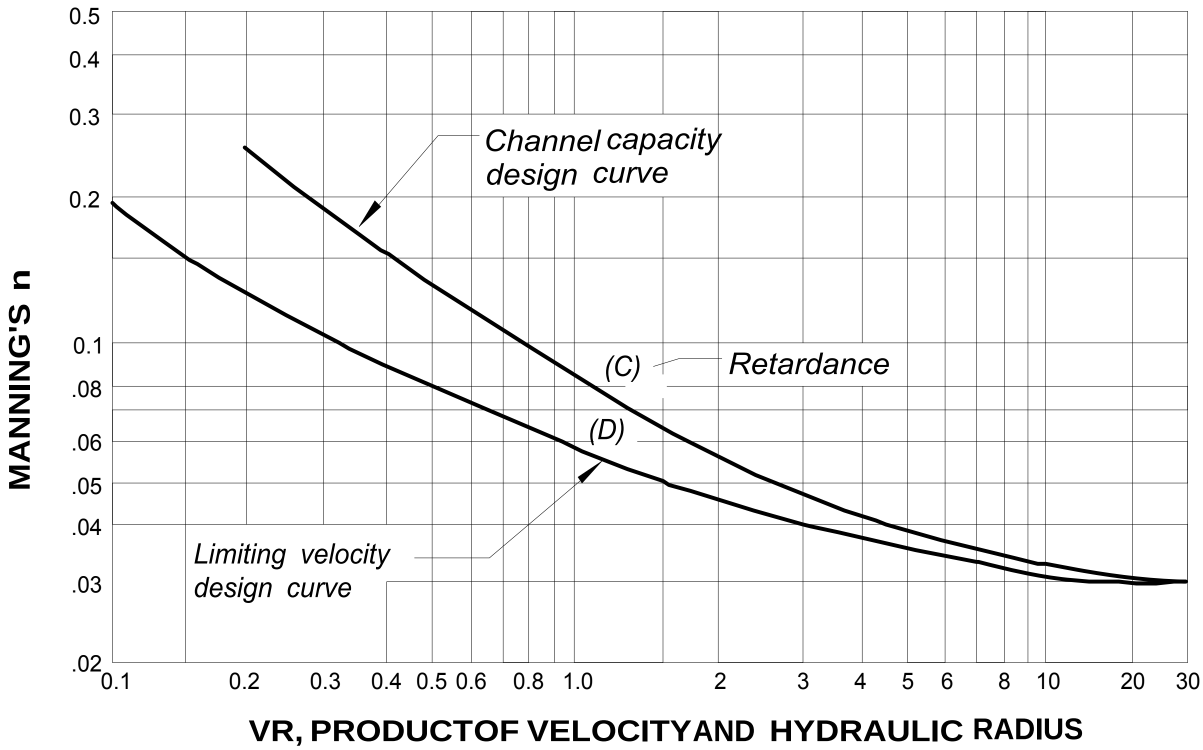


Figure MD-9a—Manning's *n* vs. Depth for Low-Flow Section in a Composite Channel.



From "Handbook of Channel Design For Soil and Water Conservation,: U.S. Department of Agriculture, Soils Conservation Service, No. SCS-TP-61 March, 1947, Rev. June, 1954

Figure MD-9b—Manning's *n* vs. *VR* for Two Retardances in Grass-Lined Channels.

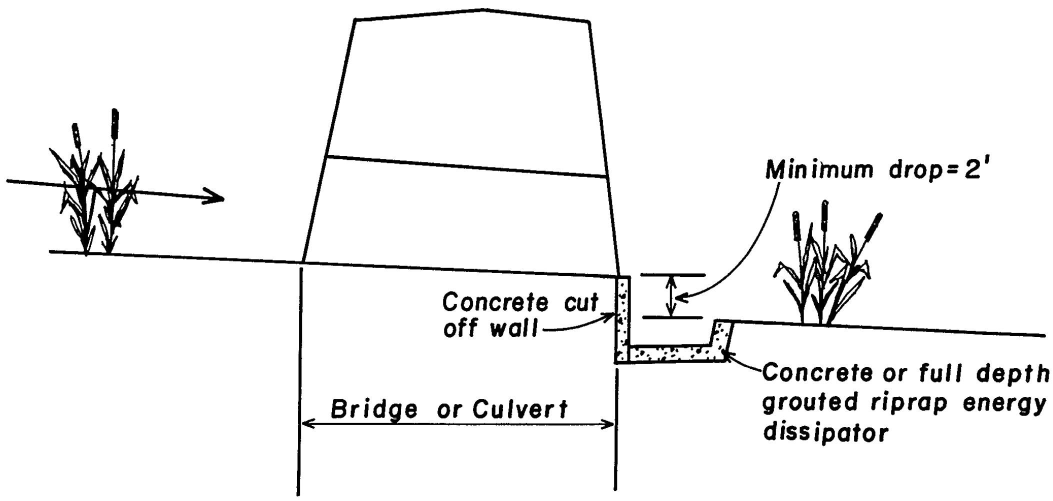


Figure MD-10—Composite (Wetland Bottom) Channel At Bridge or Culvert Crossing

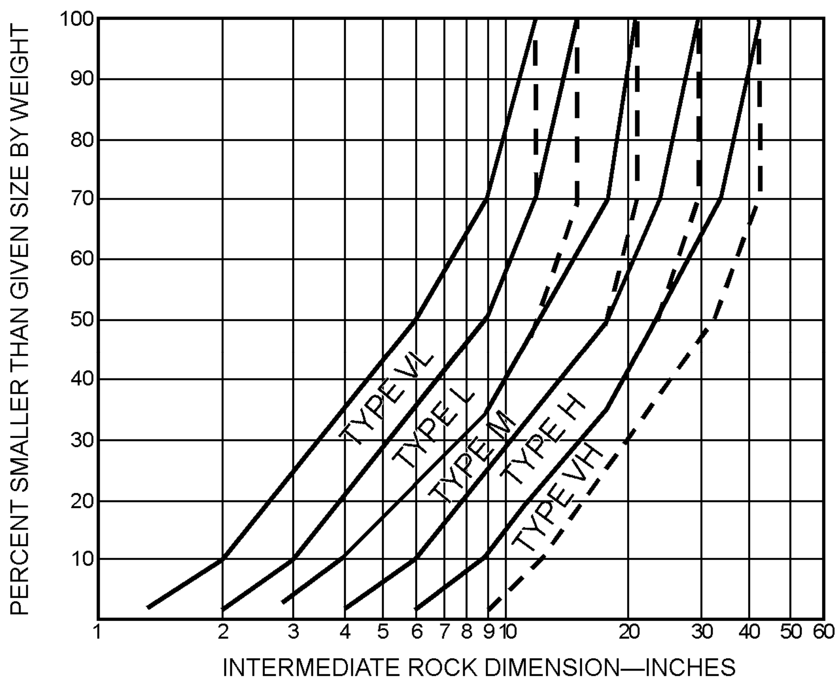


Figure MD-11—Gradation of Ordinary Riprap

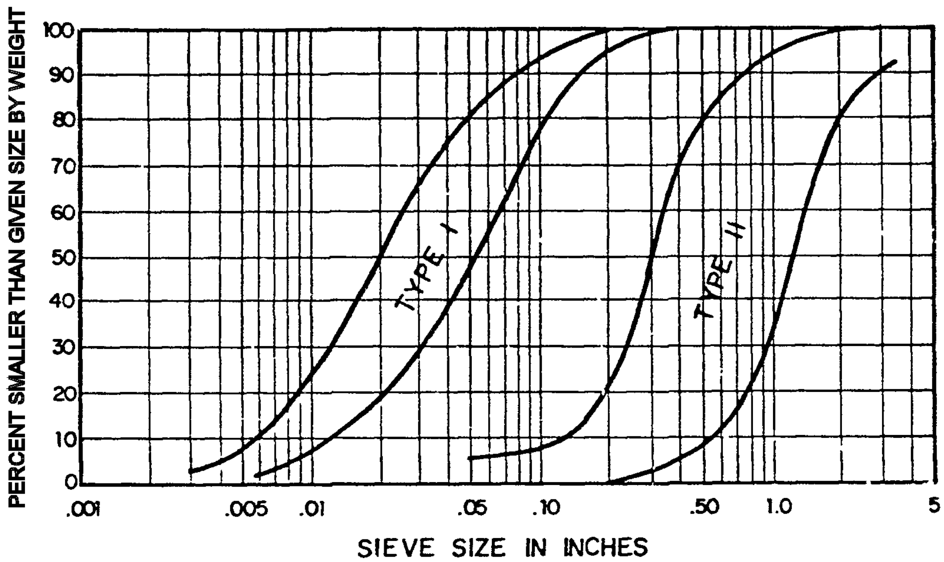
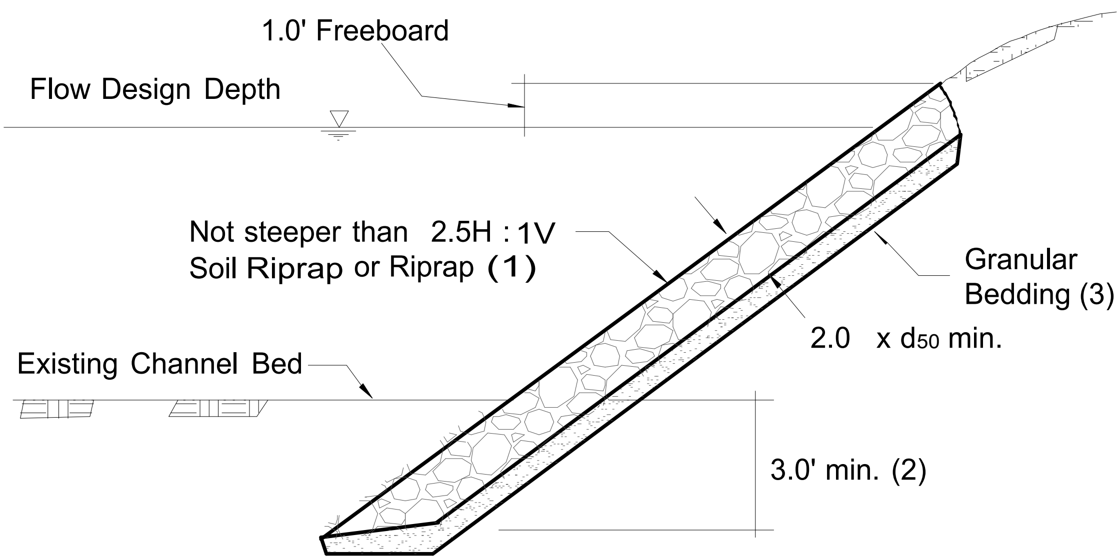


Figure MD-12—Gradation Curves for Granular Bedding

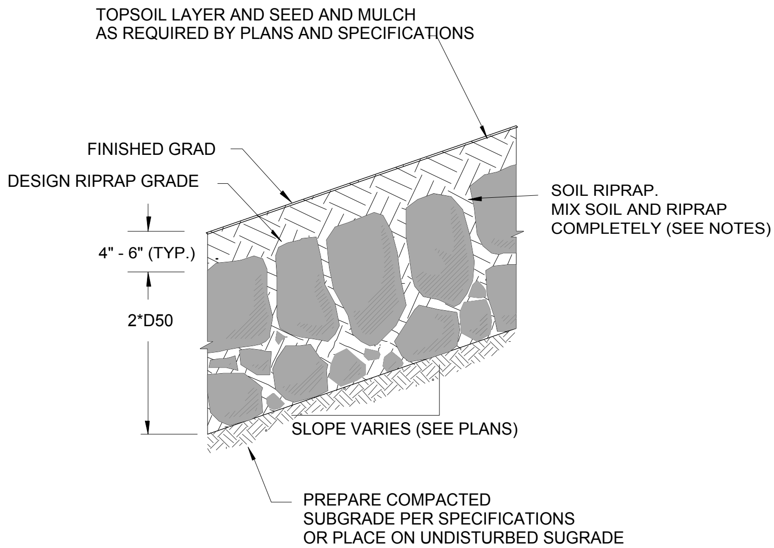


(1) Use Soil Riprap when d_{50} is less than or equal to Type M. (Suggest use of Soil Riprap for larger riprap sizes as well)

(2) 5 - feet minimum in sandy or erosive soils.

(3) Eliminate granular bedding when soil-riprap is used.

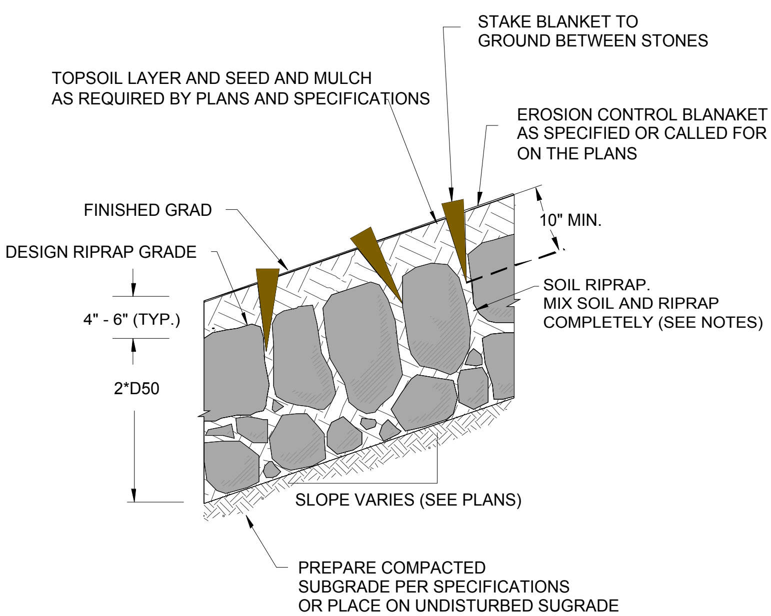
Figure MD-13a—Riprap Channel Bank Lining, Including Toe Protection

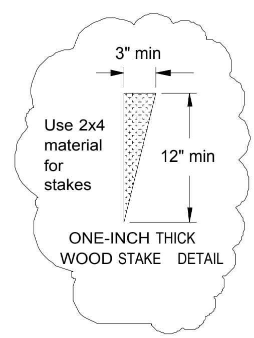


TYPICAL SECTION -
SOIL RIPRAP WITH MUCLH

NOTES:

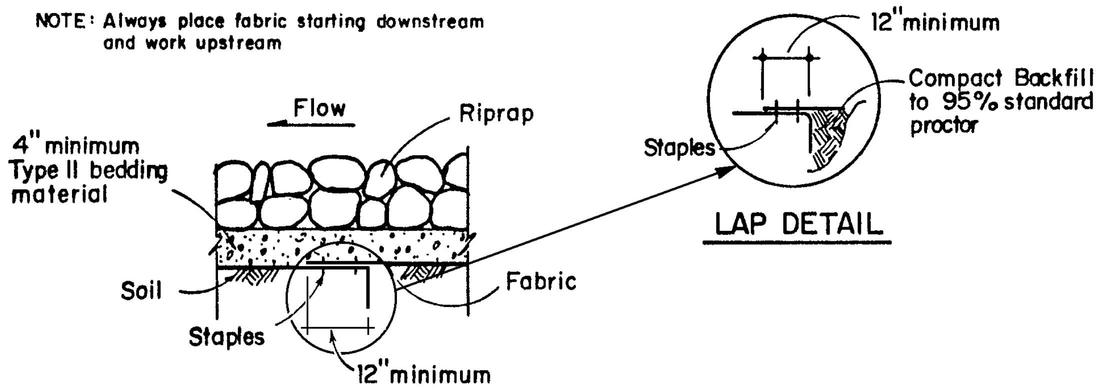
1. SOIL RIPRAP DETAILS ARE APPLICABLE TO SLOPED AREAS. REFER TO THE SITE PLAN ACTUAL LOCATION AND LIMITS.
2. MIX UNIFORM ALLY 65% RIPRAP BY VOLUME WITH 35% OF APPROVED SOIL BY VOLUME PRIOR TO PLACEMENT.
3. PLACE STONE-SOIL MIX TO RESULT IN SECURELY INTERLOCKED ROCK AT THE DESIGN THICKNESS AND GRADE. COMPACT AND LEVEL TO ELIMINATE ALL VOIDS AND ROCKS PROJECTING ABOVE DESIGN RIPRAP TOP GRADE.
4. CRIMP OR TACKIFY MULCH OR USE APPROVED HYDROMULCH AS CALLED FOR IN THE PLANS AND SPECIFICATIONS.



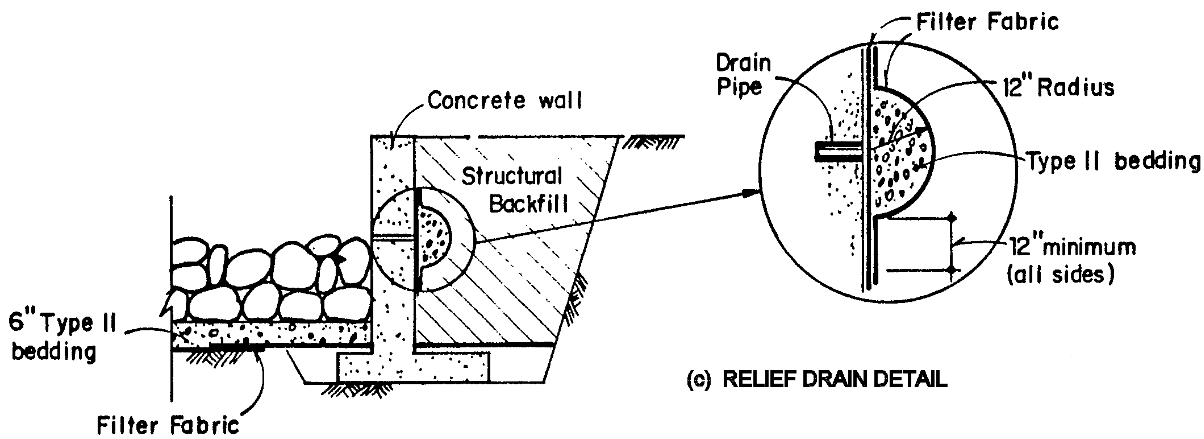


TYPICAL SECTION -
SOIL RIPRAP WITH EROSION CONTROL FABRIC

Figure MD-13b—Soil Riprap Typical Details



(a) TYPICAL LAP DETAIL AND FILTER FABRIC PLACEMENT



(c) RELIEF DRAIN DETAIL

Figure MD-14—Filter Fabric Details

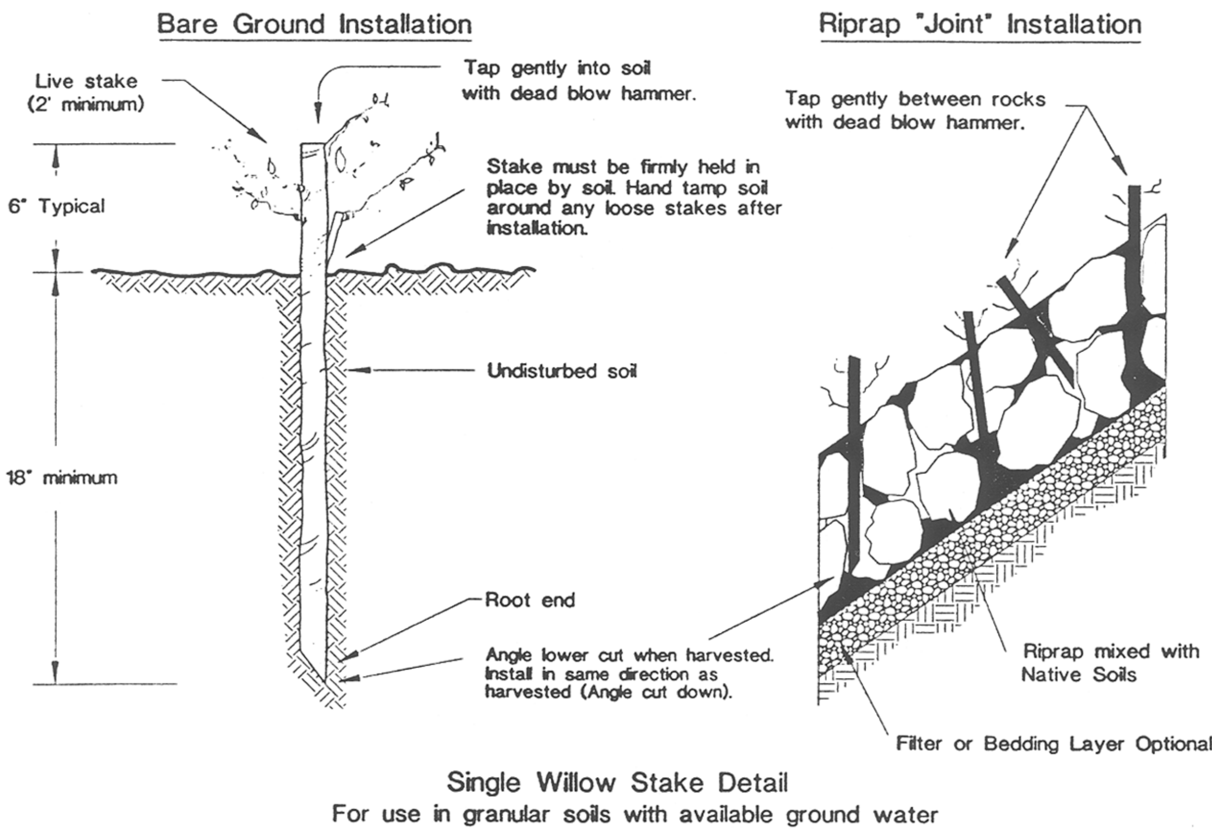


Figure MD-15—Live Willow Staking for Bare Ground and Joint Installation

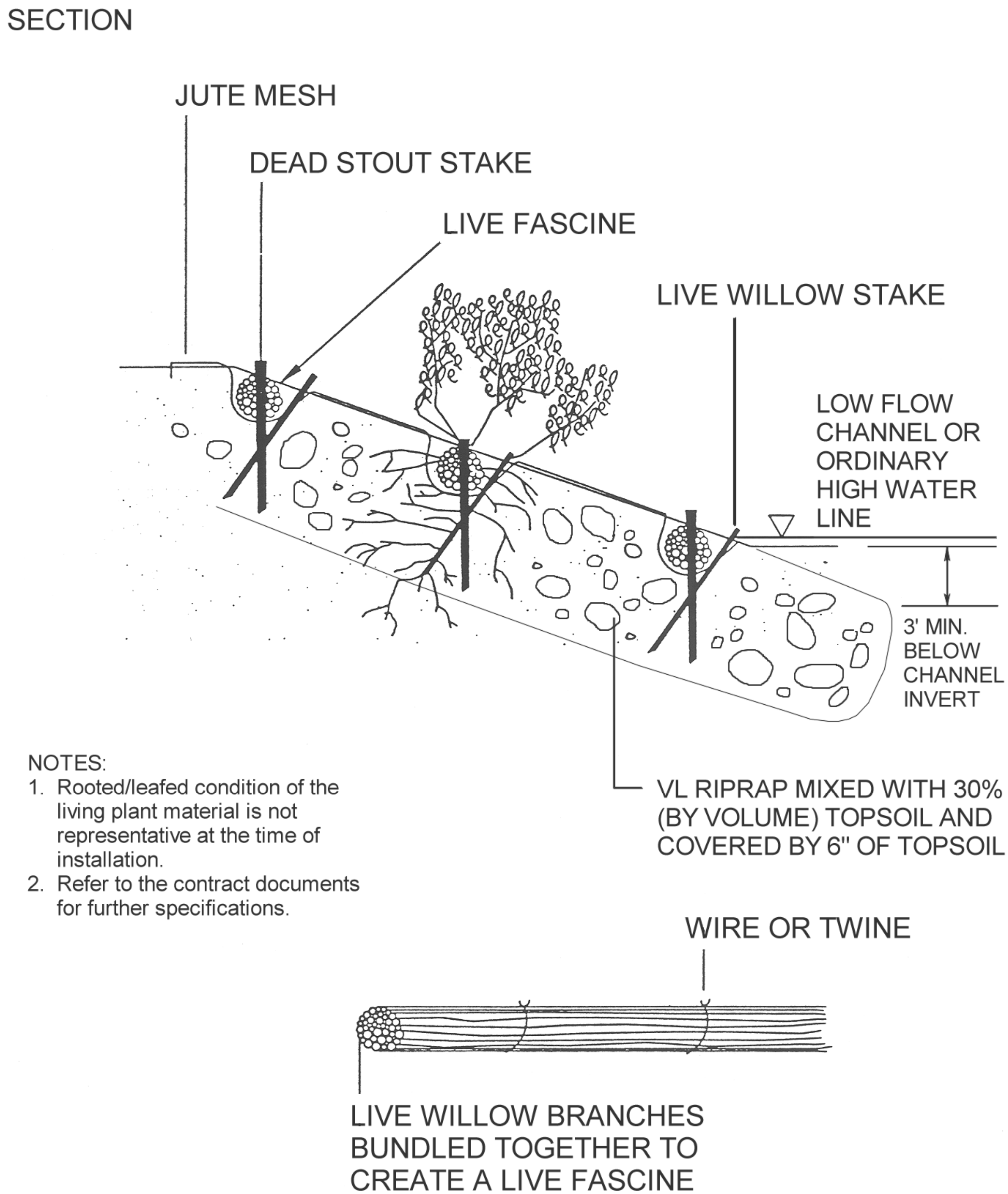
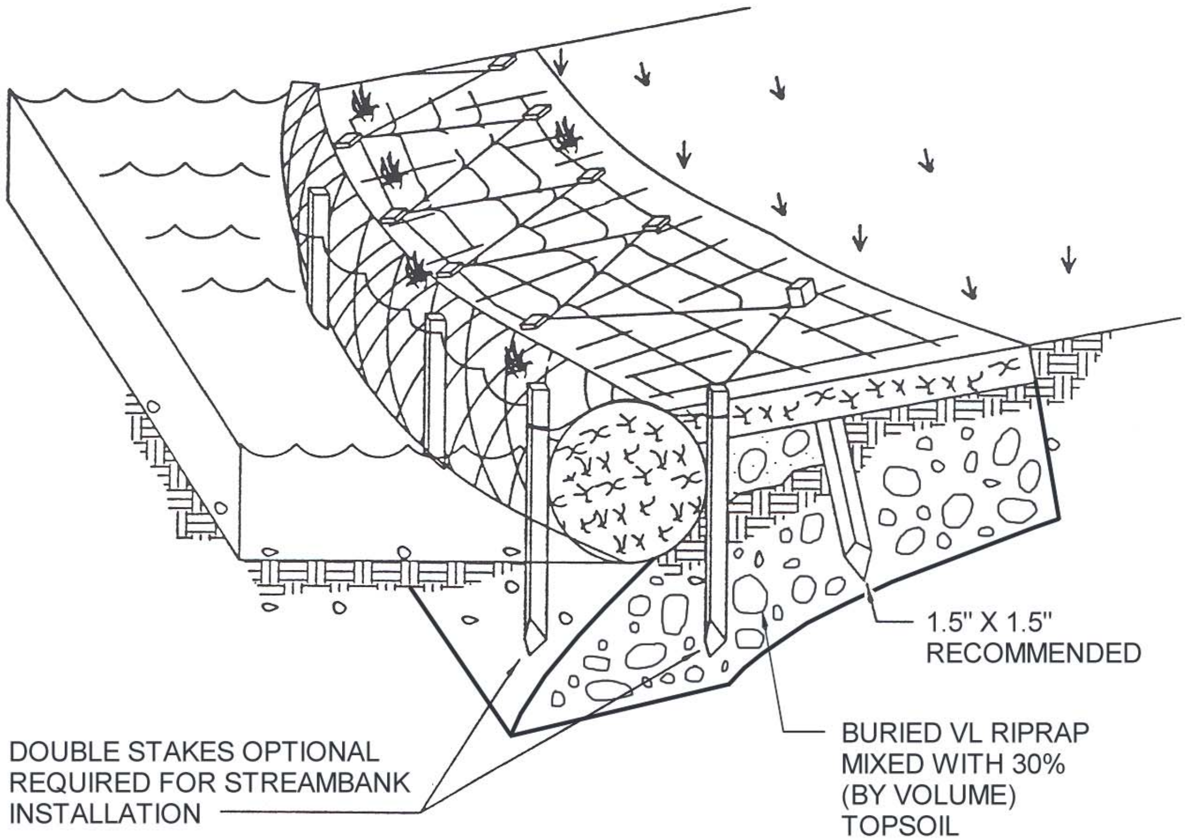


Figure MD-16—Fascine in Conjunction With Jute Mesh Mat

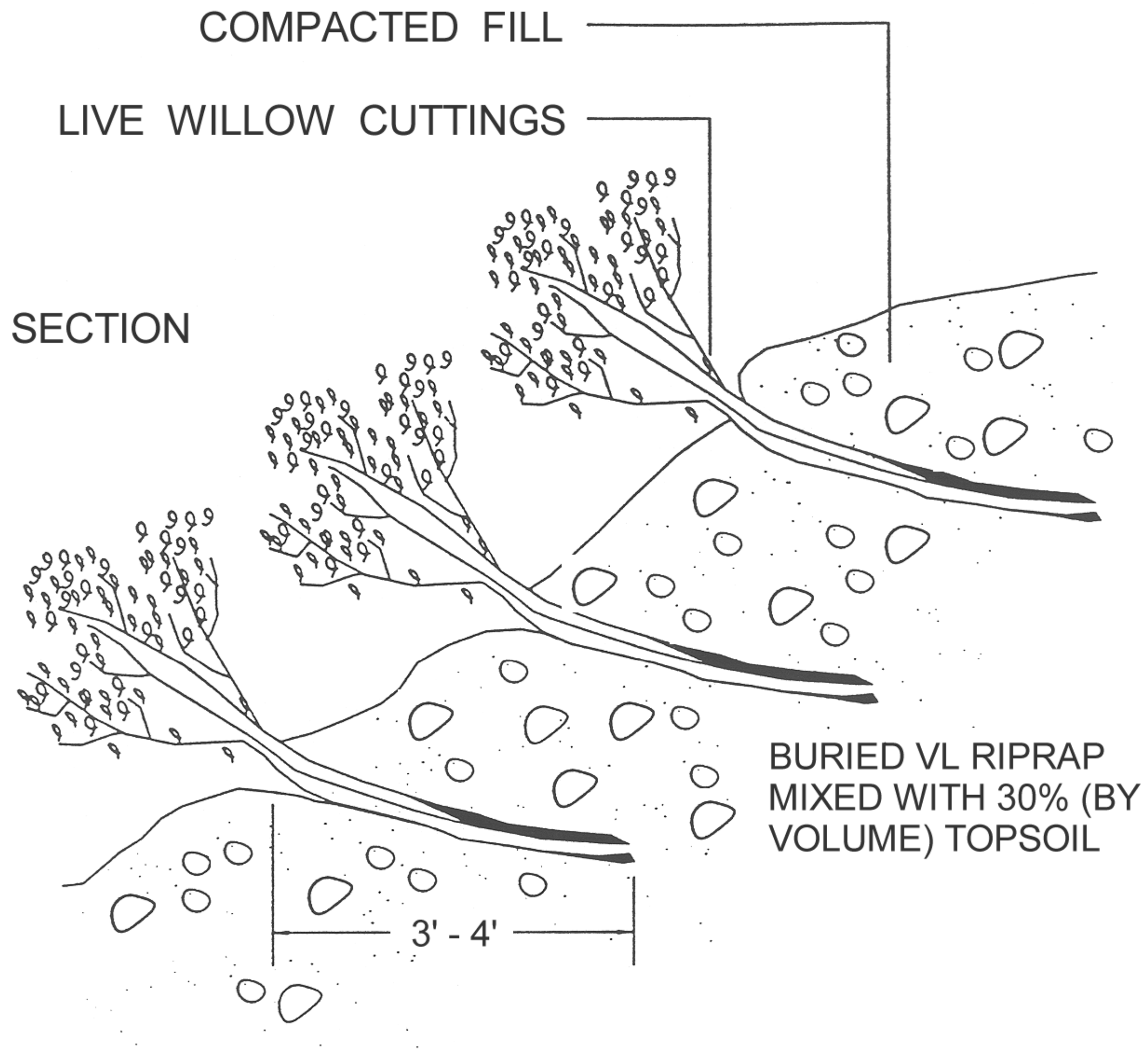


NOTES:

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 MD-17—Fiber Roll



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 details.

Figure MD-18—Brush Layering with Willow Cuttings

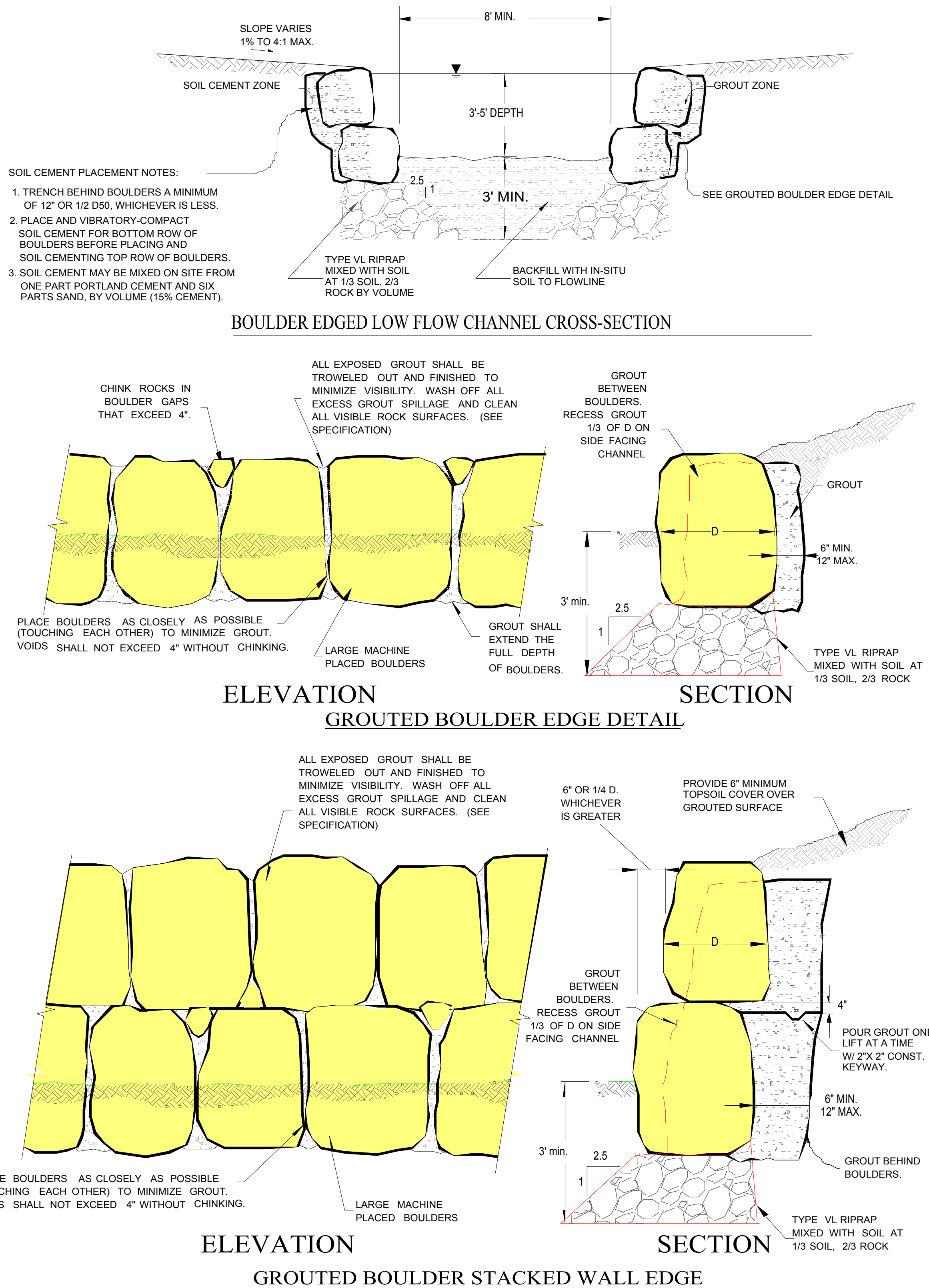


Figure MD-19—Details for Boulder Edge Treatment of a Low-Flow Channel

5.0 RECTANGULAR CONDUITS

The use of rectangular conduits of larger capacity can sometimes have cost advantages over large-diameter pipe. Furthermore, because they can be poured in place, advantages accrue in being able to incorporate conflicting utilities into the floor and roof of the structure.

Major disadvantages of rectangular conduits as storm sewers are:

1. The conduit's capacity drops significantly when the water surface reaches its roof since the wetted perimeter dramatically increases. The drop is 20% for a square cross section and more for a rectangular cross section where the width is greater than the height.

2. Normal structural design, because of economics, usually does not permit any significant interior pressures, meaning that if the conduit reached a full condition and the capacity dropped, there could be a failure due to interior pressures caused by a choking of the capacity (Murphy 1971).

It is apparent that the use of long rectangular conduits for outfall purposes requires a high standard of planning and design involving complex hydraulic considerations.

The chapters on CULVERTS and HYDRAULIC STRUCTURES in this *Manual* contain information that should be used to supplement this section in development of designs.

5.1 Hydraulic Design

Rectangular conduits are often considered as a covered free-flow conduit. They are open channels with a cover (Smith 1974). Computational procedures for flow in rectangular conduits are essentially the same as for canals and lined channels, except that special consideration is needed in regard to rapidly increasing flow resistance when a long conduit becomes full. The reader is referred to the chapters on CULVERTS and HYDRAULIC STRUCTURES for additional information.

An obstruction, or even a confluence with another conduit, may cause the flow in a near-full rectangular conduit to strike the roof and choke the capacity. The capacity reduction may then cause the entire upstream reach of the conduit to flow full, with a resulting surge and pressure head increase of sufficient magnitude to cause a structural failure. Thorough design is required to overcome this inherent potential problem. Structural design must account for internal pressure if pressure will exist.

Structural requirements and efficiency for sustaining external loads, rather than hydraulic efficiency, usually control the shape of the rectangular conduit. In urban drainage use, a rectangular conduit should usually have a straight alignment and should not decrease in size or slope in a downstream direction. It is desirable to have a slope that increases in a downstream direction as an added safety factor against it flowing full. This is particularly important for supercritical velocities that often exist in long conduits. For flatter-sloped conduits, the sediment deposition problem must be considered to prevent loss of capacity.

Roughness coefficients from Table MD-15 should be chosen carefully because of their effect on proper operation of the conduit. Quality control is important during construction; attention must be paid to grinding off projections and keeping good wall alignment. When using precast box sections, joint alignment, sealing and grouting are especially important.

Bedding and cover on conduits are structural considerations, and specifications for bedding and cover are closely allied to the loads and forces used in the structural design.

Table MD-15—Roughness Coefficients for Large Concrete Conduits

Type of Concrete Conduit	Roughness Coefficient
Precast concrete pipe, excellent joint alignment	0.012
Precast concrete pipe, ordinary joint alignment	0.013
Poured-in-place steel forms, projections 1/8” or less	0.013
Poured-in-place smooth wood forms, projections 1/8” or less	0.013
Poured-in-place ordinary work with steel forms	0.014
Poured-in-place ordinary work with wood forms	0.015

5.1.1 Entrance

Because a long rectangular conduit is costly, as well as for other reasons, the hydraulic characteristics at the entrance are particularly important. A conduit that cannot flow at the design discharge because of an inadequate or clogged inlet represents wasted investment and can result in flooding of homes, buildings, structures, and other urban infrastructure.

The entrances take on a special degree of importance for rectangular conduits, however, because the flow must be limited to an extent to ensure against overcharging the conduit. Special maximum-flow limiting entrances are often used with rectangular conduits. These special entrances should reject flow over the design discharge so that, if a runoff larger than the design flow occurs, the excess water will flow via other routes, often overland. A combined weir-orifice design is useful for this purpose. Model tests are needed for dependable design (Murphy 1971).

A second function of the entrance should be to accelerate the flow to the design velocity of the conduit, usually to meet the velocity requirements for normal depth of flow in the upstream reach of the conduit.

Air vents are needed at regular intervals to obviate both positive and negative pressures and to permit released entrained air to readily escape from the conduit.

5.1.2 Internal Pressure

The allowable internal pressure in a rectangular conduit is limited by structural design. Often, internal pressures are limited to no more than 2 to 4 feet of head before structural failure will commence, if structural design has not been based on internal pressure. Surges or conduit capacity choking cannot normally be tolerated.

5.1.3 Curves and Bends

The analysis of curves in rectangular conduits is critical to insure its hydraulic capacity. When water surface (normal, standing or reflecting waves) reaches the roof of the conduit hydraulic losses increase significantly and the capacity drops. Superelevation of the water surface must also be investigated, and allowances must be made for a changing hydraulic radius, particularly in high-velocity flow. Dynamic loads created by the curves must be analyzed to assure structural integrity for the maximum flows. See the HYDRAULIC STRUCTURES chapter of this *Manual*.

5.1.4 Transitions

Transitions provide complex hydraulic problems and require specialized analyses. Transitions, either contracting or expanding, are important with most large outfall conduits because of high-velocity flow. The development of shock waves that continue downstream can create significant problems in regard to proper conduit functioning. The best way to study transitions is through model tests (Fletcher and Grace 1972). Analytical procedures can only give approximate results. Poor transitions can cause upstream problems with both subcritical and supercritical flow, and can cause unnecessary flooding. Criteria given in the HYDRAULIC STRUCTURES chapter of this *Manual* may be used as a guide to certain limitations.

5.1.5 Air Entrainment

Entrained air causes a swell in the volume of water and an increase in depth than can cause flow in the conduit to reach the height of the roof with resulting loss of capacity; therefore, hydraulic design must account for entrained air. In rectangular conduits and circular pipes, flowing water will entrain air at velocities of about 20 ft/sec and higher. Additionally, other factors such as entrance condition, channel roughness, distance traveled, channel cross section, and volume of discharge all have some bearing on air entrainment. Volume swell can be as high as 20% (Hipschman 1970).

5.1.6 Major Inlets

Major inlets to a rectangular conduit at junctions or large storm inlets should receive a rigorous hydraulic analysis to assure against mainstream conduit flow striking the top of the rectangular conduit due to momentum changes in the main flow body as a result of the introduction of additional flow. Model tests may be necessary.

5.1.7 Sedimentation

The conduit must be designed to obviate sediment deposition problems during storm runoff events that have a frequency of occurrence of about twice each year. That is, at least twice per year, on average, the storm runoff velocity should be adequate to scour deposited sediment from the box section.

5.2 Appurtenances

The appurtenances to a long rectangular conduit are dictated by the individual needs of the particular project. Most appurtenances have some effect upon the overall operation of the system; the designer must consider all of these effects.

5.2.1 Energy Dissipators

Long conduits usually have high exit velocities that must be slowed to avoid downstream problems and damage. Energy dissipators are nearly always required. See the HYDRAULIC STRUCTURES chapter of this *Manual*.

5.2.2 Access Manholes

A long rectangular conduit should be easy to inspect, and, therefore, access manholes are desirable at various locations. If a rectangular conduit is situated under a curb, the access manholes may be combined with the storm sewer system inlets. Manholes should be aligned with the vertical wall of the box to allow rungs in the riser and box to be aligned.

Access manholes and storm inlets are useful for permitting air to flow in and out of a rectangular conduit as filling and emptying of the conduit occurs. They might also be considered safety water ejection ports should the conduit ever inadvertently flow full and cause a pileup of water upstream. The availability of such ejection ports could very well save a rectangular conduit from serious structural damage.

5.2.3 Vehicle Access Points

A large rectangular conduit with a special entrance and an energy dissipater at the exit may need an access hole for vehicle use in case major repair work becomes necessary. A vehicle access point might be a large, grated opening just downstream from the entrance. This grated opening can also serve as an effective air breather for the conduit. Vehicles may be lowered into the conduit by a crane or A-frame.

5.2.4 Safety

See discussion on public safety design consideration in the CULVERTS chapter.

5.2.5 Air Venting

Whenever it is suspected the conduit could operate at Froude Number higher than 0.7 during any flow that is at the design flow and flows lower than the design flow, or when the headwater at the conduits entrance is above the top of the conduit, the engineer has to consider installation of adequate air vents along the conduit. These are necessary to minimize major pressure fluctuations that can occur should the flow becomes unstable. When instabilities occur, air is trapped and less-than-atmospheric pressures have been shown to occur intermittently which air vents can mitigate and reduce structural loads and fluctuating hydraulic capacity in the conduit.

6.0 LARGE PIPES

Large pipes are often used as underground outfall conduits. An advantage of using pipes (circular conduits) rather than rectangular conduits is that pipes can withstand internal pressure to a greater degree than rectangular conduits can. Thus, the hydraulic design is not as critical, and a greater safety factor exists from the structural standpoint. Unless the designer is competent, experienced in open-channel hydraulics, and prepared to utilize laboratory model tests as a design aid, large pipes should be used rather than rectangular conduits. Cost differentials for the project should be carefully weighed before choosing the type of outfall conduit.

Disadvantages may include the fact that large pipes are less adaptable to an existing urban street where conflicts may exist with sanitary sewer pipes and other utilities.

6.1 Hydraulic Design

Large pipes are also considered as covered free-flow conduits; they are open channels with a cover (Steven, Simons, and Lewis 1971). Computational procedures for flow in large pipes are essentially the same as for canals and lined channels, except that consideration is given to diminishing capacity as the pipe flow nears the full depth.

Large pipes lend themselves to bends and slope changes more readily than do rectangular conduits. In a situation with a large pipe with the slope increasing in a downstream direction, there is no reason that the downstream pipe cannot be made smaller than the upstream pipe. However, the required transitional structure may rule out the smaller pipe from an economic standpoint. Improper necking down of large pipes has been a contributing factor in significant flooding of urban areas.

To aid in the solution of uniform flow computations for large pipes, see Table MD-16. The background and use of the table are similar to that given in Section 3.1.1 for open channels. Figures MD-2 and MD-3 are also useful aids for flow computations in pipes. Figure MD-20 is given as an additional design aid example. Curves presented in the STREETS/INLETS/STORM SEWERS and CULVERTS chapters of this *Manual* are also helpful in studying flow in large pipes.

Table MD-16—Uniform Flow in Circular Sections Flowing Partially Full

(Hipschman 1970)

y_0 = depth of flow
D = diameter of pipe
A = area of flow
R = hydraulic radius
Q = discharge in cfs by Manning formula
n = Manning coefficient
S_0 = slope of channel bottom and of the water surface

y_0/D	A/D^2	R/D	$Qn/(D^{8/3}S_0^{1/2})$	$Qn/(y_0^{8/3}S_0^{1/2})$	y_0/D	A/D^2	R/D	$Qn/(D^{8/3}S_0^{1/2})$	$Qn/(y_0^{8/3}S_0^{1/2})$
0.01	0.0013	0.0066	0.00007	15.040	0.51	0.4027	0.2531	0.23900	1.442
0.02	0.0037	0.0132	0.00031	10.570	0.52	0.4127	0.2562	0.24700	1.415
0.03	0.0069	0.0197	0.00074	8.560	0.53	0.4227	0.2592	0.25500	1.388
0.04	0.0105	0.0262	0.00138	7.380	0.54	0.4327	0.2621	0.26300	1.362
0.05	0.0147	0.0325	0.00222	6.550	0.55	0.4426	0.2649	0.27100	1.336
0.06	0.0192	0.0389	0.00328	5.950	0.56	0.4526	0.2676	0.27900	1.311
0.07	0.0242	0.0451	0.00455	5.470	0.57	0.4625	0.2703	0.28700	1.286
0.08	0.0294	0.0513	0.00604	5.090	0.58	0.4724	0.2728	0.29500	1.262
0.09	0.0350	0.0575	0.00775	4.760	0.59	0.4822	0.2753	0.30300	1.238
0.10	0.0409	0.0635	0.00967	4.490	0.60	0.4920	0.2776	0.31100	1.215
0.11	0.0470	0.0695	0.01181	4.250	0.61	0.5018	0.2799	0.31900	1.192
0.12	0.0534	0.0755	0.01417	4.040	0.62	0.5115	0.2821	0.32700	1.170
0.13	0.0600	0.0813	0.01674	3.860	0.63	0.5212	0.2842	0.33500	1.148
0.14	0.0668	0.0871	0.01952	3.690	0.64	0.5308	0.2862	0.34300	1.126
0.15	0.0739	0.0929	0.02250	3.540	0.65	0.5404	0.2882	0.35000	1.105
0.16	0.0811	0.0985	0.02570	3.410	0.66	0.5499	0.2900	0.35800	1.084
0.17	0.0885	0.1042	0.02910	3.280	0.67	0.5594	0.2917	0.36600	1.064
0.18	0.0961	0.1097	0.03270	3.170	0.68	0.5687	0.2933	0.37300	1.044
0.19	0.1039	0.1152	0.03650	3.060	0.69	0.5780	0.2948	0.38000	1.024
0.20	0.1118	0.1206	0.04060	2.960	0.70	0.5872	0.2962	0.38800	1.004
0.21	0.1199	0.1259	0.04480	2.870	0.71	0.5964	0.2975	0.39500	0.985
0.22	0.1281	0.1312	0.04920	2.790	0.72	0.6054	0.2987	0.40200	0.965
0.23	0.1365	0.1364	0.05370	2.710	0.73	0.6143	0.2998	0.40900	0.947
0.24	0.1449	0.1416	0.05850	2.630	0.74	0.6231	0.3008	0.41600	0.928
0.25	0.1535	0.1466	0.06340	2.560	0.75	0.6319	0.3017	0.42200	0.910
0.26	0.1623	0.1516	0.06860	2.490	0.76	0.6405	0.3024	0.42900	0.891
0.27	0.1711	0.1566	0.07390	2.420	0.77	0.6489	0.3031	0.43500	0.873
0.28	0.1800	0.1614	0.07930	2.360	0.78	0.6573	0.3036	0.44100	0.856
0.29	0.1890	0.1662	0.08490	2.300	0.79	0.6655	0.3039	0.44700	0.838
0.30	0.1982	0.1709	0.09070	2.250	0.80	0.6736	0.3042	0.45300	0.821
0.31	0.2074	0.1756	0.09660	2.200	0.81	0.6815	0.3043	0.45800	0.804
0.32	0.2167	0.1802	0.10270	2.140	0.82	0.6893	0.3043	0.46300	0.787
0.33	0.2260	0.1847	0.10890	2.090	0.83	0.6969	0.3041	0.46800	0.770
0.34	0.2355	0.1891	0.11530	2.050	0.84	0.7043	0.3038	0.47300	0.753
0.35	0.2450	0.1935	0.12180	2.000	0.85	0.7115	0.3033	0.47700	0.736
0.36	0.2546	0.1978	0.12840	1.958	0.86	0.7186	0.3026	0.48100	0.720
0.37	0.2642	0.2020	0.13510	1.915	0.87	0.7254	0.3018	0.48500	0.703
0.38	0.2739	0.2062	0.14200	1.875	0.88	0.7320	0.3007	0.48800	0.687
0.39	0.2836	0.2102	0.14900	1.835	0.89	0.7384	0.2995	0.49100	0.670
0.40	0.2934	0.2142	0.15610	1.797	0.90	0.7445	0.2980	0.49400	0.654
0.41	0.3032	0.2182	0.16330	1.760	0.91	0.7504	0.2963	0.49600	0.637
0.42	0.3130	0.2220	0.17050	1.724	0.92	0.7560	0.2944	0.49700	0.621
0.43	0.3229	0.2258	0.17790	1.689	0.93	0.7612	0.2921	0.49800	0.604
0.44	0.3328	0.2295	0.18540	1.655	0.94	0.7662	0.2895	0.49800	0.588
0.45	0.3428	0.2331	0.19290	1.622	0.95	0.7707	0.2865	0.49800	0.571
0.46	0.3527	0.2366	0.20100	1.590	0.96	0.7749	0.2829	0.49600	0.553
0.47	0.3627	0.2401	0.20800	1.559	0.97	0.7785	0.2787	0.49400	0.535
0.48	0.3727	0.2435	0.21600	1.530	0.98	0.7817	0.2735	0.49800	0.517
0.49	0.3827	0.2468	0.22400	1.500	0.99	0.7841	0.2666	0.48300	0.496
0.50	0.3927	0.2500	0.23200	1.471	1.00	0.7854	0.2500	0.46300	0.463

6.1.1 Entrance

The longer a pipe is, the more important is design of the entrance. A large pipe unable to flow at the design capacity represents wasted investment. Acceleration of flow, typically to the design velocity of the pipe reach immediately downstream, is often an important characteristic of the entrance. Typically air vents are necessary immediately downstream of the entrance to allow entrained air to escape and to act as breathers should less-than-atmospheric pressures develop in the pipe. Long pipes that depend on flow entering at upstream points other than street inlets need to be equipped with adequately sized safety/trash racks at the entrances. For guidance on sizing safety/trash racks, see guidance in the CULVERTS chapter.

6.1.2 Internal Pressure

The allowable internal pressure is limited by the structural design of the pipe; however, it is not as critical as with rectangular conduits, with up to perhaps 25 feet of head being permissible in some pipe designs before failure commences. It is evident, however, that large pipe outfalls cannot be designed for flow under any significant pressure because then inflow from other lines could not enter, and water would flow out of storm inlets rather than into these inlets. The internal pressure aspect is important only as a safety factor in the event of a choking of capacity or an inadvertent flow surcharge.

6.1.3 Curves and Bends

Curves and bends are permitted, but detailed analysis is required to ensure structural integrity and proper hydraulic functioning of the conduit. Maintenance access should be provided in the proximity of all bends. Hydraulic analyses are important at locations where hydraulic jumps may occur.

6.1.4 Transitions

Transitions are discussed in the HYDRAULIC STRUCTURES chapter of this *Manual*.

6.1.5 Air Entrainment and Venting

The reader is referred to Sections 5.1.5 and 5.2.5 of this chapter.

6.1.6 Major Inlets

Inflow to the conduit can cause unanticipated hydraulic variations; however, the analytical approach need not be as rigorous as with rectangular conduits.

6.2 Appurtenances

The reader is referred to Section 5.2 of this chapter.

6.3 Safety

See guidance in the CULVERTS chapter.

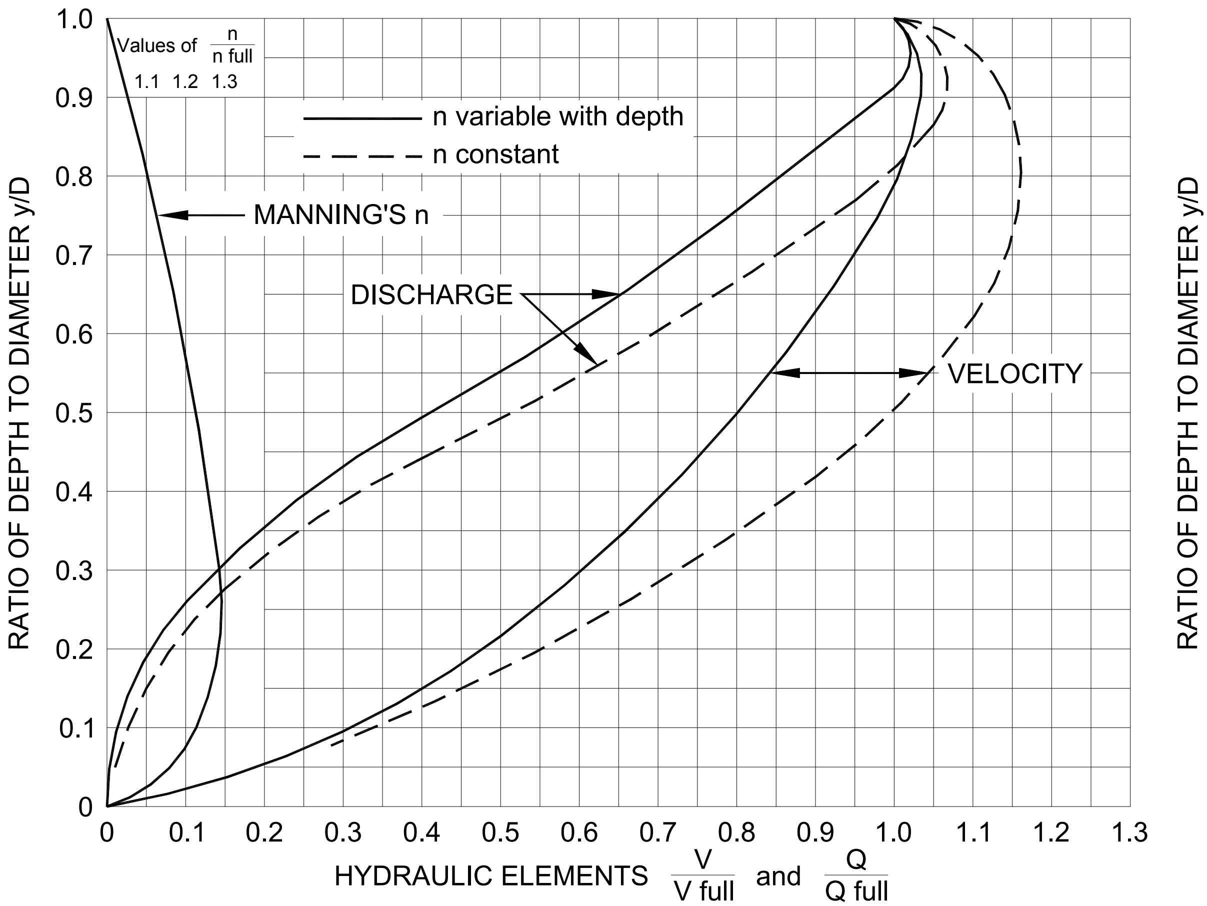


Figure MD-20—Hydraulic Properties of Pipes

(Steven, Simons, and Lewis 1976)

7.0 PROTECTION DOWNSTREAM OF PIPE OUTLETS

This section is intended to address the use of riprap for erosion protection downstream of conduit and culvert outlets that are in-line with major drainageway channels. Inadequate protection at conduit and culvert outlets has long been a major problem. The designer should refer to Section 4.4 for additional information on major drainage applications utilizing riprap. In addition, the criteria and guidance in Section 4.4 may be useful in design of erosion protection for conduit outlets. The reader is referred to Section 7.0 of the HYDRAULIC STRUCTURES chapter of this *Manual* for information on rundowns, and to Section 3.0 of the HYDRAULIC STRUCTURES chapter for additional discussion on culvert outfall protection.

Scour resulting from highly turbulent, rapidly decelerating flow is a common problem at conduit outlets. The riprap protection design protocol is suggested for conduit and culvert outlet Froude numbers up to 2.5 (i.e., Froude parameters $Q/d_0^{2.5}$ or $Q/WH^{1.5}$ up to 14 $ft^{0.5}$/sec) where the channel and conduit slopes are parallel with the channel gradient and the conduit outlet invert is flush with the riprap channel protection. Here, Q is the discharge in cfs, d_0 is the diameter of a circular conduit in feet and W and H are the width and height, respectively, of a rectangular conduit in feet.

7.1 Configuration of Riprap Protection

Figure MD-25 illustrates typical riprap protection of culverts and major drainageway conduit outlets. The additional thickness of the riprap just downstream from the outlet is to assure protection from flow conditions that might precipitate rock movement in this region.

7.2 Required Rock Size

The required rock size may be selected from Figure MD-21 for circular conduits and from Figure MD-22 for rectangular conduits. Figure MD-21 is valid for $Q/D_c^{2.5}$ of 6 or less and Figure MD-22 is valid for $Q/WH^{1.5}$ of 8.0 or less. The parameters in these two figures are:

1. $Q/D^{1.5}$ or $Q/WH^{0.5}$ in which Q is the design discharge in cfs, D_c is the diameter of a circular conduit in feet, and W and H are the width and height of a rectangular conduit in feet.

2. Y_t/D_c or Y_t/H in which Y_t is the tailwater depth in feet, D_c is the diameter of a circular conduit in feet, and H is the height of a rectangular conduit in feet. In cases where Y_t is unknown or a hydraulic jump is suspected downstream of the outlet, use Y_t/D_t = Y_t/H = 0.40 when using Figures MD-21 and MD-22.

3. The riprap size requirements in Figures MD-21 and MD-22 are based on the non-dimensional parametric Equations MD-18 and MD-19 (Steven, Simons, and Lewis 1971 and Smith 1975).

   Circular culvert:

$$\frac{\left(\frac{d_{50}}{D_c}\right)\left(\frac{Y_t}{D_c}\right)^{1.2}}{\left(\frac{Q}{D_c^{2.5}}\right)} = 0.023 \qquad \text{(MD-18)}$$

   Rectangular culvert:

$$\frac{\left(\frac{d_{50}}{H}\right)\left(\frac{Y_t}{H}\right)}{\left(\frac{Q}{WH^{1.5}}\right)} = 0.014 \qquad \text{(MD-19)}$$

The rock size requirements were determined assuming that the flow in the culvert barrel is not supercritical. It is possible to use Equations MD-18 and MD-19 when the flow in the culvert is supercritical (and less than full) if the value of D_c or H is modified for use in Figures MD-21 and MD-22. Whenever the flow is supercritical in the culvert, substitute D_a for D_c and H_a for H, in which D_a is defined as:

$$D_a = \frac{(D_c + Y_n)}{2} \qquad \text{(MD-20)}$$

in which the maximum value of D_a shall not exceed D, and

$$H_a = \frac{(H + Y_n)}{2} \qquad \text{(MD-21)}$$

in which the maximum value of H_a shall not exceed H, and:

D_a = parameter to use in place of D in Figure MD-21 when flow is supercritical

D_c = diameter of circular culvert (ft)

H_a = parameter to use in place of H in Figure MD-22 when flow is supercritical

H = height of rectangular culvert (ft)

Y_n = normal depth of supercritical flow in the culvert

7.3 Extent of Protection

The length of the riprap protection downstream from the outlet depends on the degree of protection desired. If it is necessary to prevent all erosion, the riprap must be continued until the velocity has been reduced to an acceptable value. For purposes of outlet protection during major floods, the acceptable velocity is set at 5.5 ft/sec for very erosive soils and at 7.7 ft/sec for erosion resistant soils. The rate at which the velocity of a jet from a conduit outlet decreases is not well known. For the procedure recommended here, it is assumed to be related to the angle of lateral expansion, θ, of the jet. The velocity is related to the expansion factor, $(1/(2\tan\theta))$, which can be determined directly using Figure MD-23 or Figure MD-24, assuming that the expanding jet has a rectangular shape:

$$L_p = \left(\frac{1}{2\tan\theta}\right)\left(\frac{A_t}{Y_t} - W\right) \quad \text{(MD-22)}$$

where:

L_p = length of protection (ft)

W = width of the conduit in (ft) (use diameter for circular conduits)

Y_t = tailwater depth (ft)

θ = the expansion angle of the culvert flow

and:

$$A_t = \frac{Q}{V} \quad \text{(MD-23)}$$

where:

Q = design discharge (cfs)

V = the allowable non-eroding velocity in the downstream channel (ft/sec)

A_t = required area of flow at allowable velocity (ft²)

In certain circumstances, Equation MD-22 may yield unreasonable results. Therefore, in no case should L_p be less than $3H$ or $3D$, nor does L_p need to be greater than $10H$ or $10D$ whenever the Froude parameter, $Q/WH^{1.5}$ or $Q/D^{2.5}$, is less than 8.0 or 6.0, respectively. Whenever the Froude parameter is greater than these maximums, increase the maximum L_p required by ¼ D_c or ¼ H for circular or rectangular culverts, respectively, for each whole number by which the Froude parameter is greater than 8.0 or 6.0, respectively.

7.4 Multiple Conduit Installations

The procedures outlined in Sections 7.1, 7.2, and 7.3 can be used to design outlet erosion protection for multi-barrel culvert installations by hypothetically replacing the multiple barrels with a single hydraulically equivalent rectangular conduit. The dimensions of the equivalent conduit may be established as follows:

1. Distribute the total discharge, Q, among the individual conduits. Where all the conduits are hydraulically similar and identically situated, the flow can be assumed to be equally distributed; otherwise, the flow through each barrel must be computed.

2. Compute the Froude parameter $Q_i/D_{ci}^{2.5}$ (circular conduit) or $Q_i/W_iH_i^{1.5}$ (rectangular conduit), where the subscript i indicates the discharge and dimensions associated with an individual conduit.

3. If the installation includes dissimilar conduits, select the conduit with the largest value of the Froude parameter to determine the dimensions of the equivalent conduit.

4. Make the height of the equivalent conduit, H_{eq}, equal to the height, or diameter, of the selected individual conduit.

5. The width of the equivalent conduit, W_{eq}, is determined by equating the Froude parameter from the selected individual conduit with the Froude parameter associated with the equivalent conduit, $Q/W_iH_{eq}^{1.5}$.

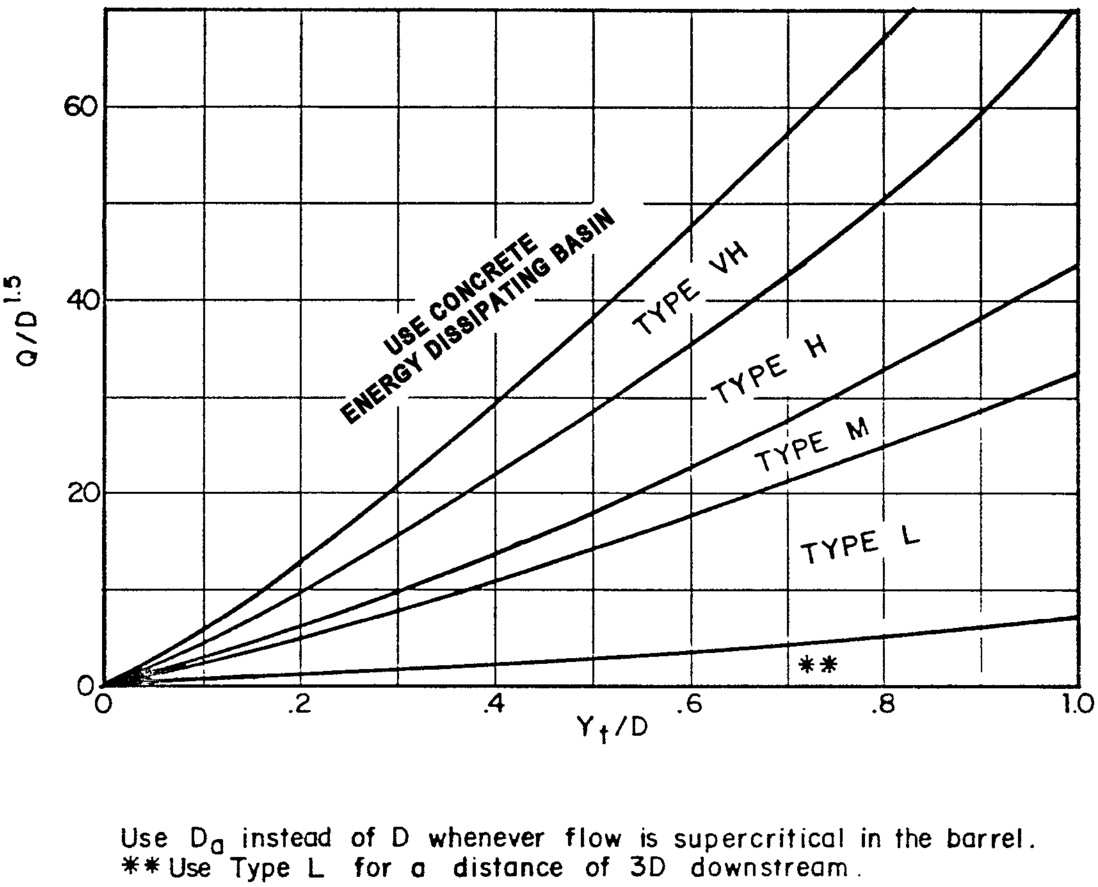
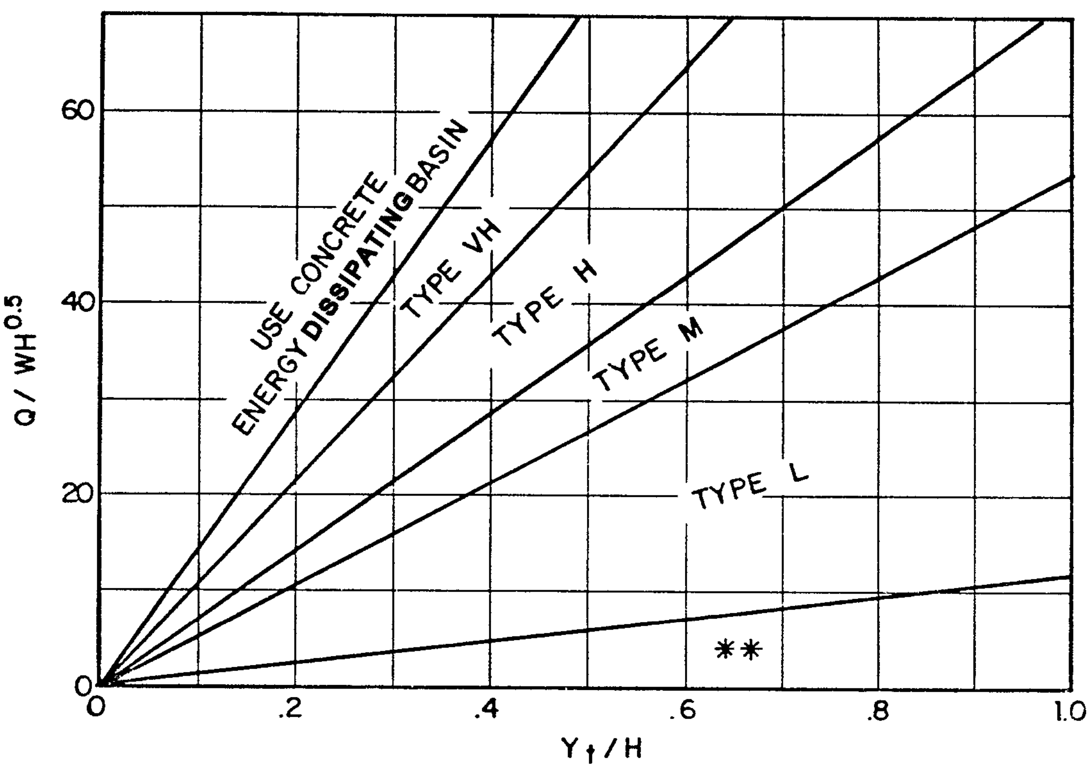


Figure MD-21—Riprap Erosion Protection at Circular Conduit Outlet Valid for $Q/D^{2.5} \leq 6.0$



Use H_a instead of H whenever culvert has supercritical flow in the barrel.
**Use Type L for a distance of 3H downstream.

Figure MD-22—Riprap Erosion Protection at Rectangular Conduit Outlet Valid for $Q/WH^{1.5} \leq 8.0$

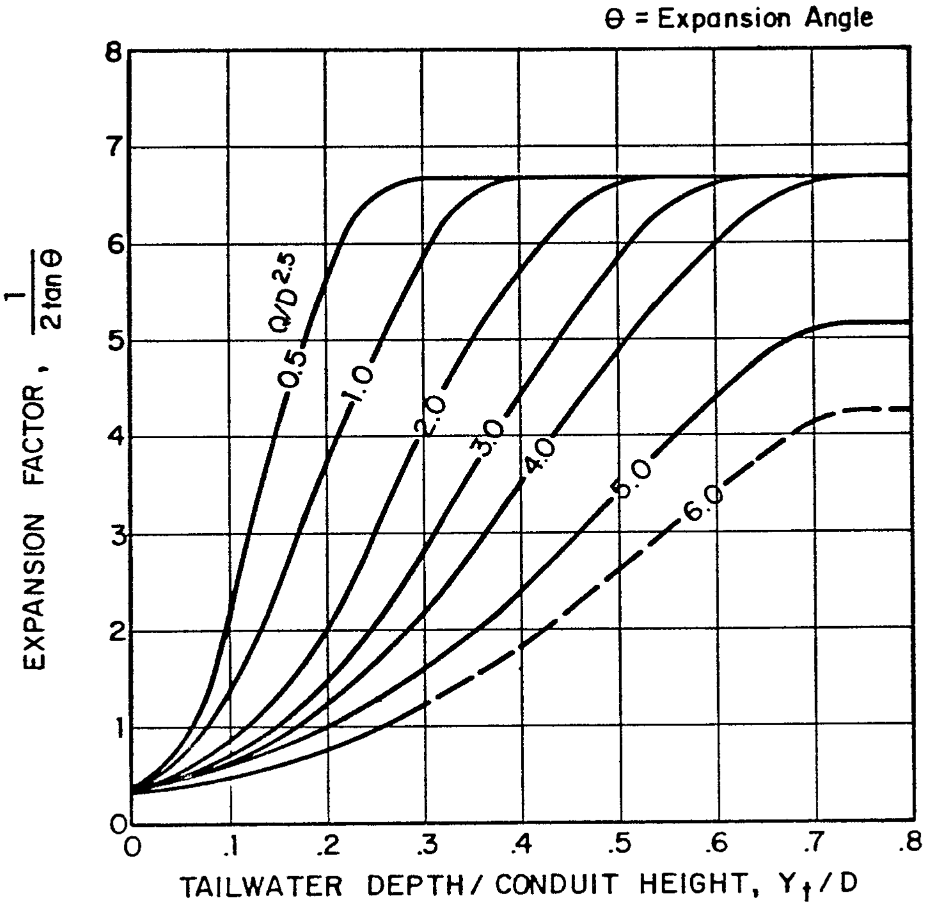


Figure MD-23—Expansion Factor for Circular Conduits

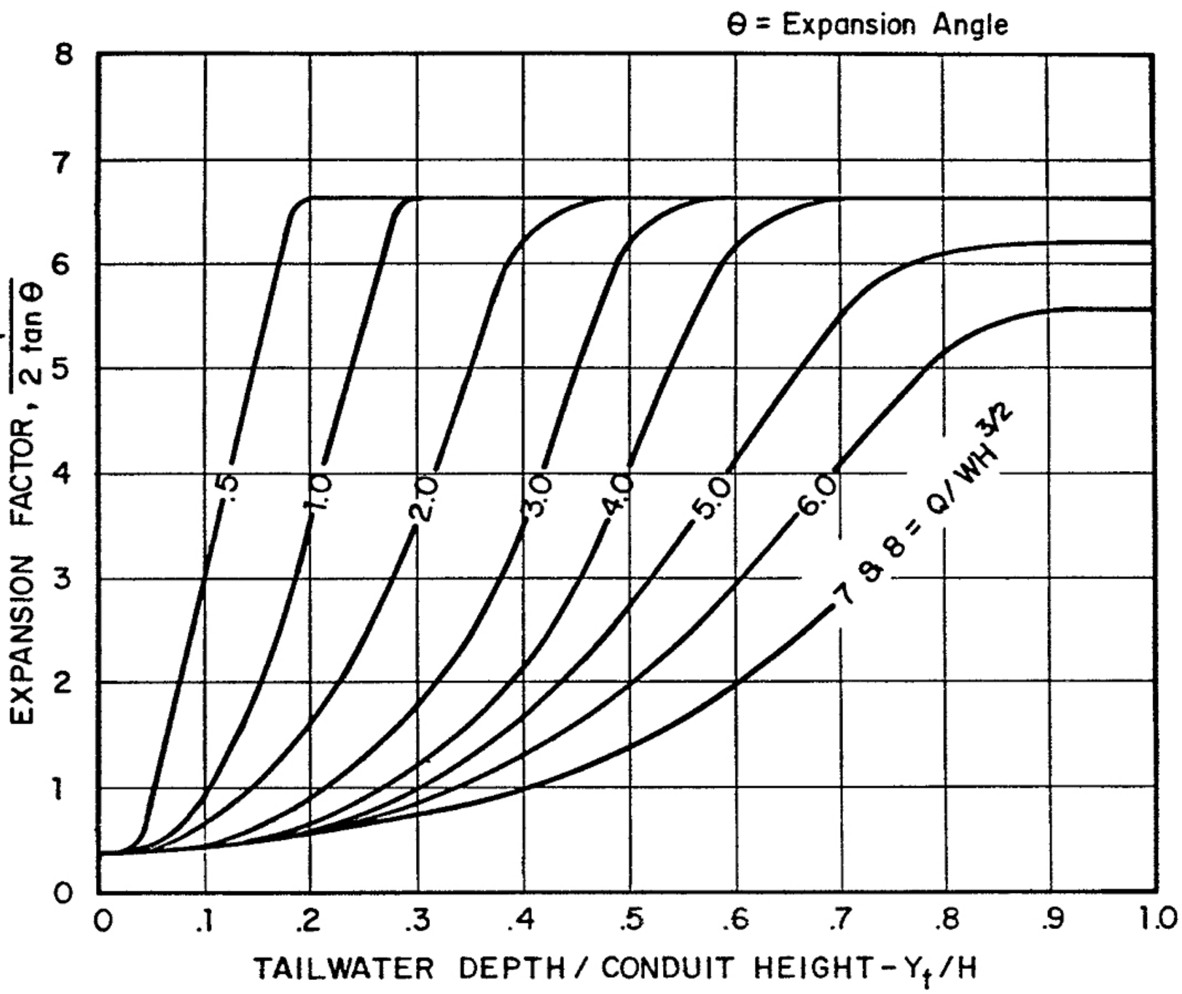
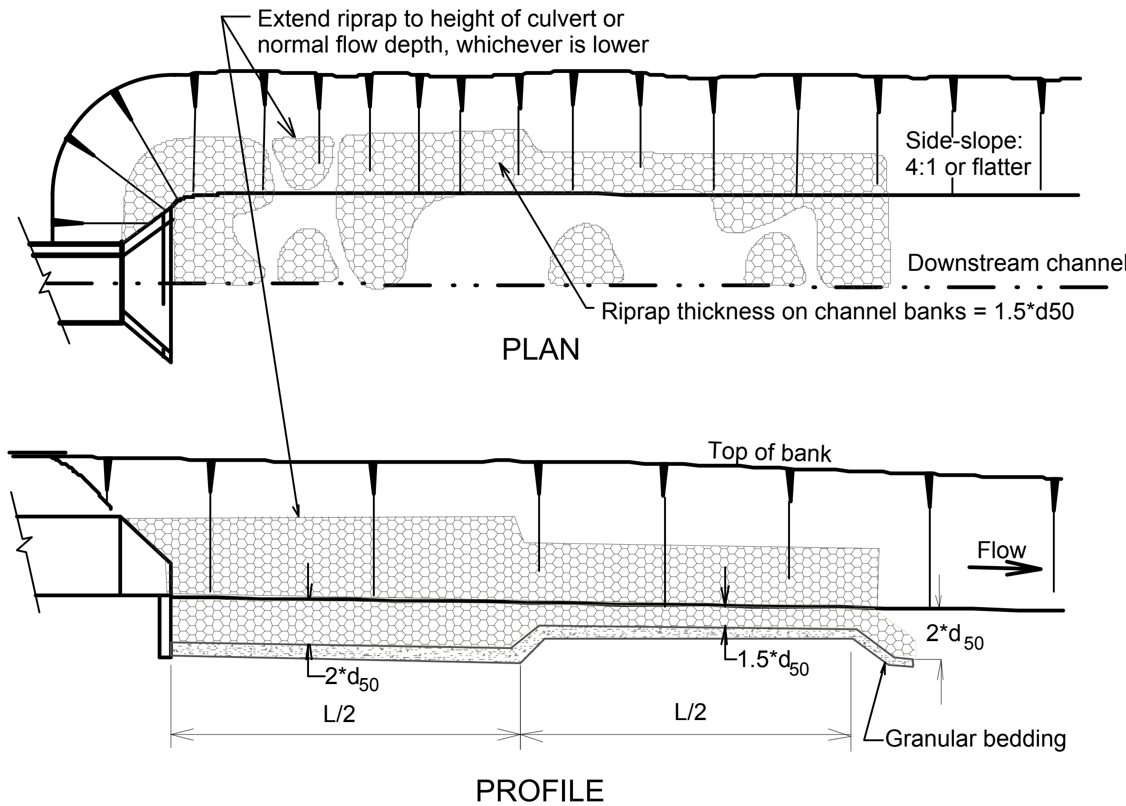


Figure MD-24—Expansion Factor for Rectangular Conduits



NOTES: 1. Headwall with wingwalls or flared end section required at all culvert outlets.
2. Cutoff wall required at end of wingwall aprons and end section.
Minimum depth of cutoff wall = 2*d50 or 3-feet, whichever is deeper.
3. Provide joint fasteners for flared end sections.

Figure MD-25—Culvert and Pipe Outlet Erosion Protection

8.0 SEDIMENT

Well-established urban areas are not significant sediment producers. However, winter sanding operations, new construction areas, and usual residential storm runoff will provide some sediment to the drainage system, which must be acknowledged. One of the greatest sedimentation problems occurs, however, when an area is undergoing urbanization. Furthermore, in a grass-lined channel or a natural channel, erosion will typically occur in some reaches of the channel and sediment will generally deposit in other reaches. Sedimentation is a problem in urban drainage hydrology in that, if the channel is made steep enough to transport all sediment, the velocities will also be high enough to cause erosion that would not otherwise occur if the channel was flatter. Often the designer must make the choice to have a well-planned and designed channel which will transport the minimal sediment yield in the future, realizing that the initial operation of the channel will result in sediment deposition during the process of urbanization.

The designer would be well advised to give full consideration to the sediment deposition problem and to utilize sediment deposition basins at selected locations along channels and at stormwater runoff entry points into channels for periodic sediment removal when it is obvious that there will be substantial sediment inflow, at least initially. In addition, the designer can include sediment storage and trap areas within flood detention basins and retention ponds to great advantage. See the chapter on STORAGE in this *Manual*.

In a grass-lined channel, particularly after the grass has obtained maturity, fine sediment will settle out regularly on top of the sod. Over a period of years, there will be a gradual buildup of the channel bottom, many times imperceptible, but nonetheless occurring. Because of the frequent use of drops in grass-lined channels as well as natural channels, the build-up rate will decrease with time. However, if aggradation tends to reduce the capacity of the channel, periodic restorative maintenance work will need to be performed to re-establish the design depth.

The subject of sedimentation design cannot be completely covered in this *Manual* because of its complexity. Volume 3 of the *Manual* addresses suspended sediment in greater detail, but little guidance is given for bedload since its presence is dependant on many factors (i.e., construction activities upstream, channel bank line erosion, channel bed degradation, use of erosion control practices, etc.). As a rule of thumb, velocities of 3.0 ft/sec will transport sediments up to the size of fine sands. However, being able to achieve these velocities during minor runoff events throughout the channel’s cross section may not be feasible.

9.0 EXAMPLES

9.1 Example MD-1: Normal Depth Calculation with Normal Worksheet

This example involves determination of channel capacity and other relevant hydraulic parameters for a grass-lined trapezoidal channel flowing at normal depth, given the following channel characteristics and constraints:

Channel Characteristics:

So = channel bottom slope (longitudinal slope) = 0.3%

Z = Z1 = Z2 = channel side slopes (left and right) = 4H:1V

n = Manning's n (grass-lined channel) = 0.035

B = bottom width = 10 ft

Constraints:

Y = maximum allowable depth of flow in channel = 5.0 ft

F = freeboard required = 2.0 ft

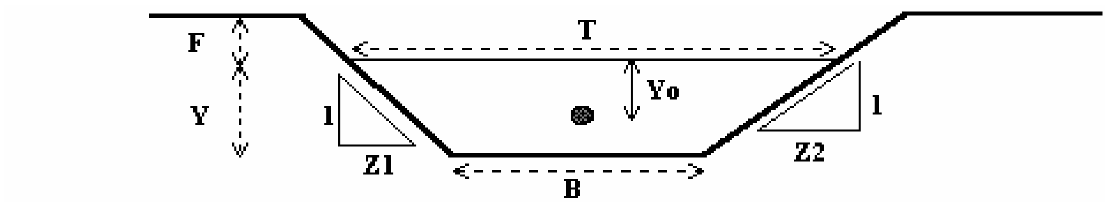
A sketch of the channel cross section, which defines these parameters, is included as a part of the worksheet and is illustrated for this example on the calculation sheet on the following page.

These channel characteristics and sizing constraints are entered into the input section of the *Basic* worksheet of the UD-Channels Spreadsheet to determine discharge using normal depth calculations. A worksheet demonstrating application of the *Basic Worksheet* titled "Normal Flow Analysis—Trapezoidal Channel" for "Project = Example MD-1" and "Channel ID = Normal Depth Example" is provided as an example of normal depth analysis.

Based on this analysis, the channel would be capable of carrying a flow of approximately 700 cfs, given a total bank height of 7 ft to allow for the required freeboard. In addition, the calculations indicate that flow will be subcritical under these conditions. Since the velocity is close to the 5.0 ft/sec maximum allowable 100-year velocity for grass-lined channels with erosive soils, the spreadsheet should be reapplied using a lower Manning's n value to see if the maximum velocity criterion is exceeded.

Normal Flow Analysis - Trapezoidal Channel

Project: **Example MD-1**
Channel ID: **Normal Depth Exampl**



Design Information (Input)			
Channel Invert Slope	So =	0.003	ft/ft
Manning's n	n =	0.035	
Bottom Width	B =	10	ft
Left Side Slope	Z1 =	4	ft/ft
Right Side Slope	Z2 =	4	ft/ft
Freeboard Height	F =	2	ft
Design Water Depth	Y =	5	ft

Normal Flow Condtion (Calculated)			
Discharge	**Q =**	**715.83**	cfs
Froude Number	**Fr =**	**0.49**	
Flow Velocity	**V =**	**4.77**	fps
Flow Area	A =	150.00	sq ft
Top Width	T =	50.00	ft
Wetted Perimeter	P =	51.23	ft
Hydraulic Radius	R =	2.93	ft
Hydraulic Depth	D =	3.00	ft
Specific Energy	Es =	5.35	ft
Centroid of Flow Area	Yo =	1.93	ft
Specific Force	Fs =	24.72	kip

9.2 Example MD-2: Composite Section Calculations Using Composite Design Worksheet

This example involves calculation of channel cross-section geometry parameters for a composite channel consisting of a low-flow channel with side slope protection for conveyance of frequent flows (up to 2-year) and vegetated overbanks to accommodate larger runoff events (up to the 100-year event). In this case, criteria for a grass-lined composite channel with side slope protection for the low-flow channel are applied for sizing. The channel sizing is based on hydraulic design parameters including:

Q-2yr = 2-year discharge = 600 cfs

Q-100yr = 100-year discharge (fully-developed, un-detained condition) = 3000 cfs

Qlf = design discharge for low flow channel = 300 cfs

Z1 = low flow channel left side slope = 3H:1V

Z2 = low flow channel right side slope = 3H:1V

Ym = low flow channel bank-full depth = 3 ft

ZL = left overbank side slope = 4H:1V

N-left = left overbank Manning's n = 0.040

ZR = right overbank side slope = 4H:1V

N-right = right overbank Manning's n = 0.040

Yob = overbank flow depth = 3.0 ft

Soil type = sandy

Left overbank width as a percentage of total overbank width = 50%

A sketch of the channel cross section, which defines these parameters, is included as a part of the worksheet and is illustrated for this example on the calculation sheet on the following page.

These hydraulic parameters are entered into the input section of the **Composite Design Worksheet** of the UD-Channels Spreadsheet to determine low flow, overbank, and composite channel characteristics for the low-flow design discharge and the 100-year discharge. A worksheet demonstrating application of the **Composite Design Worksheet** titled "Design of Composite Channel" for "Project = Example MD-2" and "Channel ID = Composite Channel Example" is provided as an example of this calculation tool.

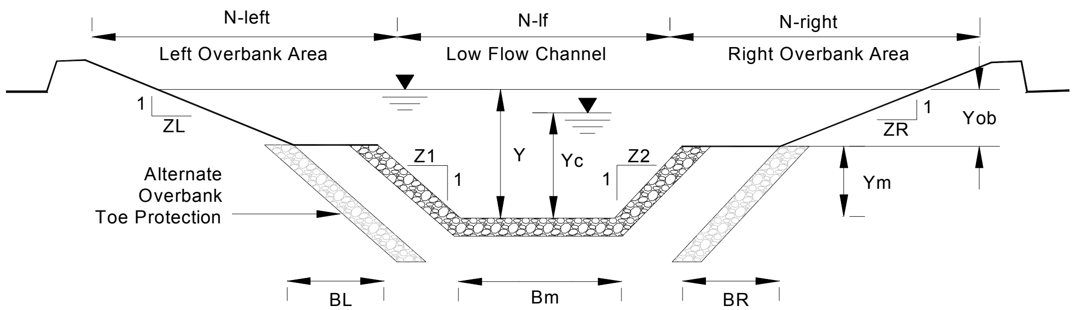
The analysis demonstrates that a channel with the characteristics specified above, an invert slope of 0.49%, a 3-foot-deep low-flow channel with a bottom width of 20.7 ft, evenly distributed overbank benches to the left and right of the low-flow channel with width = 38.6 ft, and a total top width of 139.9 ft will meet the following design criteria:

1. The low-flow channel has the capacity to convey between ⅓ to ½ of the 2-year flow at a depth not exceeding 3 ft.
2. Flow is subcritical for all flow conditions evaluated, and Fr < 0.8, thereby satisfying Froude number criterion for non-erosive soils.
3. Longitudinal channel slope ≥ 0.2% and ≤ 0.6%.
4. Maximum depth of flow outside of low flow channel < 5.0 ft.
5. Composite cross section 100-year velocity < 7.0 ft/sec (non-erosive soils).
6. 4H:1V side slopes permit maintenance of vegetated banks.

Design of Composite Channel

Project: **Example MD-2**

Channel ID: **Composite Section Calculations Using Composite Design Worksheet**



Design Information (Input)

2-Year Discharge - Total	Q-2yr =	600	cfs			
100-Year Discharge - Total	Q-100yr =	3,000	cfs	**Check one of the following toe protection types**		
Design Discharge - Low Flow Channel	Qlf =	300	cfs	Low Flow Channel Sideslope Protection	X	check, OR
Low Flow Channel Left Side Slope	Z1 =	3.0	ft/ft	Overbank Toe Protection		check
Low Flow Channel Right Side Slope	Z2 =	3.0	ft/ft			
Low Flow Channel Bank-full depth	Ym =	3.00	ft	Left overbank width as a		
Left Overbank Side Slope	ZL =	4.0	ft/ft	percentage of total overbank width	50	%
Left Overbank Manning's n	n-left =	0.0400				
Right Overbank Side Slope	ZR =	4.0	ft/ft	**Check one of the following soil types**		
Right Overbank Manning's n	n-right =	0.0400		Sandy Soil	X	check, OR
Overbank Flow Depth Yob (Y - Ym)	Yob =	3.00	ft	Non-Sandy Soil		check

Flow Condition (Calculated)

Channel Invert Slope **So =** **0.0049** **ft/ft**

Low Flow Channel Condition for Qd				**Low Flow Channel Flow Condition for Q100**			
Channel Bottom Width	Blf =	20.7	ft	Low Flow Channel Bottom Width	Bm =	20.7	ft
Channel Normal Flow Depth	Ylf =	3.00	ft	Top width	Tm =	38.7	ft
Top width	Tlf =	38.7	ft	Flow area	Am =	204.9	sq ft
Flow area	Alf =	89.0	sq ft	Wetted perimeter	Pm =	39.6	ft
Wetted perimeter	Plf =	39.6	ft	Manning's n (Calculated)	n-m =	0.0386	
Manning's n (Calculated)	n-lf =	0.0534		**Discharge**	**Qm =**	**1,667**	**cfs**
Discharge (Calculated)	**Qlf =**	**300**	**cfs**	Velocity	Vm =	8.1	fps
Velocity	Vlf =	3.4	fps	**Froude number**	**Frm =**	**0.62**	
Froude number	Fr-lf =	0.39		100-Yr. Critical Velocity	Vmc =	11.2	fps
				100-Yr. Critical Depth	Ymc =	4.6	ft

Left Overbank Flow Condition for Q100				**Right Overbank Flow Condition for Q100**			
Overbank Bench Width	BL =	38.6	ft	Overbank Bench Width	BR =	38.6	ft
Normal Depth in Overbanks	YLob =	3.0	ft	Normal Depth in Overbanks	YRob =	3.0	ft
Top width	TL =	50.6	ft	Top width	TR =	50.6	ft
Flow area	AL =	133.7	sq ft	Flow area	AR =	133.7	sq ft
Wetted perimeter	PL =	50.9	ft	Wetted perimeter	PR =	50.9	ft
Discharge	**QL =**	**668**	**cfs**	**Discharge**	**QR =**	**668**	**cfs**
Velocity	**VL =**	**5.0**	**fps**	**Velocity**	**VR =**	**5.0**	**fps**
Froude number	**FrL =**	**0.54**		**Froude number**	**FrR =**	**0.54**	
100-Yr. Critical Velocity	VLc =	7.7	fps	100-Yr. Critical Velocity	VRc =	7.7	fps
100-Yr. Critical Depth in Overbanks	YLc =	2.0	ft	100-Yr. Critical Depth in Overbanks	YRc =	2.0	ft

Composite Cross-Section Flow Condition for Q100

Top width	**T =**	**139.8**	**ft**	**Discharge**	**Q =**	**3,002**	**cfs**
Channel Depth Y	**Y =**	**6.00**	**ft**	**Velocity (average)**	**V =**	**6.4**	**fps**
Flow area	A =	472.2	sq ft	Froude number	Fr =	0.61	
Wetted perimeter	P =	141.5	ft	100-Yr. Critical Velocity	Vc =	9.0	fps
Cross-Sectional Manning's n (Calculated)	n =	0.0392		100-Yr. Critical Depth in Overbanks	Yc =	1.97	ft

NOTE:

The sum of QL + QR + Qm will slightly overestimate the total composite channel discharge, and will not equal Q. These element values are used, however, to estimate critical velocity and critical depth for design purposes.

9.3 Example MD-3: Riprap Lined Channel Calculations Using Riprap Channel Worksheet

This example demonstrates application of the **Riprap Worksheet** of the UD-Channels Spreadsheet to determine riprap sizing for a trapezoidal channel. The worksheet calculates a riprap sizing parameter based on Equation MD-13, with adjustments for channel curvature, to determine the riprap type required for the channel lining. Calculations are based on the following channel characteristics provided by the user:

So = channel invert slope = 0.010 ft/ft

B = bottom width = 30.0 ft

Z1 = left side slope = 2.5H:1V

Z2 = right side slope = 2.5H:1V

Ss = specific gravity of rock = 2.5

Ccr = radius of channel centerline = 200 ft

Q = design discharge = 2500 cfs

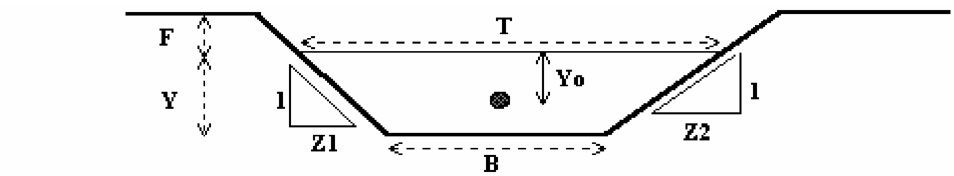
A sketch of the channel cross section, which defines these parameters, is included as a part of the worksheet and is illustrated for this example on the calculation sheet on the following page.

These parameters are entered into the input section of the **Riprap Worksheet** of the UD-Channels Spreadsheet to determine riprap type and channel hydraulic characteristics including Manning's *n*, the Froude number, velocity, and superelevation. A worksheet demonstrating application of the **Riprap Worksheet** titled "Design of Riprap Channel Cross Section" for "Project = Example MD-3" and "Channel ID = Riprap Channel Example" is provided as an example of this calculation tool.

Based on this analysis, Type H riprap is suitable for straight and curved sections of the channel and will meet the minimum K factor requirements. Calculations indicate that flow will be subcritical for the design discharge and that the Froude number is less than the maximum Froude number criterion for riprap channels of 0.8. Calculations also indicate that superelevation is not expected as a result of the channel curvature.

Design of Riprap Channel Cross Section

Project: Example MD-3
Channel ID: Rirap Channel Example



Design Information (Input)			
Channel Invert Slope	So =	0.0100	ft/ft
Bottom Width	B =	30.0	ft
Left Side Slope	Z1 =	2.5	ft/ft
Right Side Slope	Z2 =	2.5	ft/ft
Specific Gravity of Rock	Ss =	2.50	
Radius of Channel Centerline	Ccr =	200.0	ft
Design Disharge	**Q =**	**2,500.0**	**cfs**
Flow Condition (Calculated)			
Riprap Type (Straight Channel)	**Type =**	**H**	
Intermediate Rock Diameter (Straight Channel)	**D50 =**	**18**	**inches**
Calculated Manning's n (Straight Channel)	**n =**	**0.0423**	
Riprap Type (Outside Bend of Curved Channel)	**Type =**	**H**	
Intermediate Rock Dia. (O.B. of Curved Channel)	**D50 =**	**18**	**inches**
Calculated Manning's N (Curved Channel)	**n =**	**0.0423**	
Water Depth	Y =	5.97	ft
Top Width of Flow	T =	59.8	ft
Flow Area	A =	268.2	sq ft
Wetted Perimeter	P =	62.1	ft
Hydraulic Radius (A/P)	R =	4.3	ft
Average Flow Velocity (Q/A)	V =	9.3	fps
Hydraulic Depth (A/T)	D =	4.5	ft
Froude Number (max. = 0.8)	Fr =	0.78	
Channel Radius / Top Width	Ccr/T =	3.34	
Riprap Design Velocity Factor For Curved Channel	Kv =	1.69	
Riprap Sizing Velocity For Curved Channel	V_{Kv} =	15.8	fps
Riprap Sizing Paramenter for Straight Channel	**K =**	**3.27**	
Riprap Sizing Paramenter for Outside Bend of Curve	**K_{curve} =**	**5.51**	
*** Superelevation (dh)	dh =	0.41	ft
Discharge (Check)	**Q =**	**2,506.4**	**cfs**

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