Chapter 8
Open Channels

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1.0 Introduction

This chapter focuses on the preservation, enhancement, and restoration of stream corridors as well as the design of constructed channels and swales using natural concepts. Guidance is provided for the hydraulic evaluation of open channels and the design of measures to improve the stability and health of stream systems. These measures include maintaining or establishing an effective planimetric channel form, cross sectional shape, and longitudinal slope; implementing grade control and bank protection; and establishing and maintaining a favorable mix of riparian vegetation. See the *Hydraulic Structures* chapter for various types of structures with an open channels and the *Stream Access and Recreational Channels* chapter for criteria related to the design of shared use paths adjacent to streams and criteria for responsible design of recreational channels including boatable channels. This chapter is organized as follows:

Section 2.0 – Natural Stream Corridors. This section highlights the many functions and benefits of natural stream corridors then describes some of the threats to these natural systems that can be imposed by urbanization. Historically, urban impacts have included realigning or straightening streams, narrowing the width of natural floodplains, and even replacing surface streams with underground conduits. Increases in runoff as a result of urbanization have contributed to degradation, aggregation, loss of vegetation and habitat, and impaired water quality. This section introduces the concept of preserving natural stream corridors and implementing techniques to restore stream functions. See the *Planning* chapter for techniques for implementing preservation.

Section 3.0 – Preserving Natural Stream Corridors. This section recommends several key actions that are necessary at the outset of development to preserve natural stream corridors. Preservation includes providing ample room for the floodplain, reducing increases in urban runoff, and addressing problems proactively. These actions can reduce impacts and provide for future stream management at a lower cost and smaller footprint compared to constrained floodplains where elevated discharges must be conveyed in narrow corridors.

Section 4.0 –Stream Restoration Principles. Eight principles of stream restoration are discussed to provide design guidance for developers, engineers, ecologists, and others involved in the protection of stream resources. The principles are valid for a variety of stream conditions, whether the corridor has been preserved as described in Section 3.0 or constrained and impacted through urbanization. Special design considerations are recommended for constrained urban stream reaches where velocities and shear stress imposed by elevated peak discharges are greater and infrastructure tends to be in close proximity to the stream.

Section 5.0 – Naturalized Channels. Sometimes streams need to be created where adequate channel conveyances do not exist. This section applies the principles of Section 4.0 to the design of naturalized channels. When designed with natural features, these channels can become established in a form that may be indistinguishable from natural streams.

Section 6.0 – Swales. As an alternative to storm drains, it is often desirable to create small surface channels, or swales, to convey runoff from small drainage areas. This section provides guidance for the design of grass and rock (soil riprap or void-filled riprap) swales.

Section 7.0 – Hydraulic Analysis. This section provides guidance on the hydraulic analysis of natural and constructed stream systems, emphasizing the use of HEC-RAS for hydraulic modeling.

Section 8.0 – Rock and Boulders. The use of soil riprap, void-filled riprap, and boulders in stream restoration and constructed channels is addressed in this section.

2.0 Natural Stream Corridors

Natural stream corridors, as illustrated in Figure 8-1, often contain a primarily non-vegetated bankfull channel that may flow continuously or ephemerally within adjacent vegetated floodplain terraces (also called benches or overbanks) and higher outer banks. An appropriately sized single-thread channel with floodplain terraces creates favorable conditions at baseflows, producing greater depth, lower temperatures, and better aquatic habitat. The spilling of flows out of the bankfull channel onto wider floodplain terraces provides important interaction between water, soil, and vegetation. As floodwaters spread out onto the floodplain terraces, energy is dissipated, riparian vegetation receives water, and sediment can be conveyed through the system.

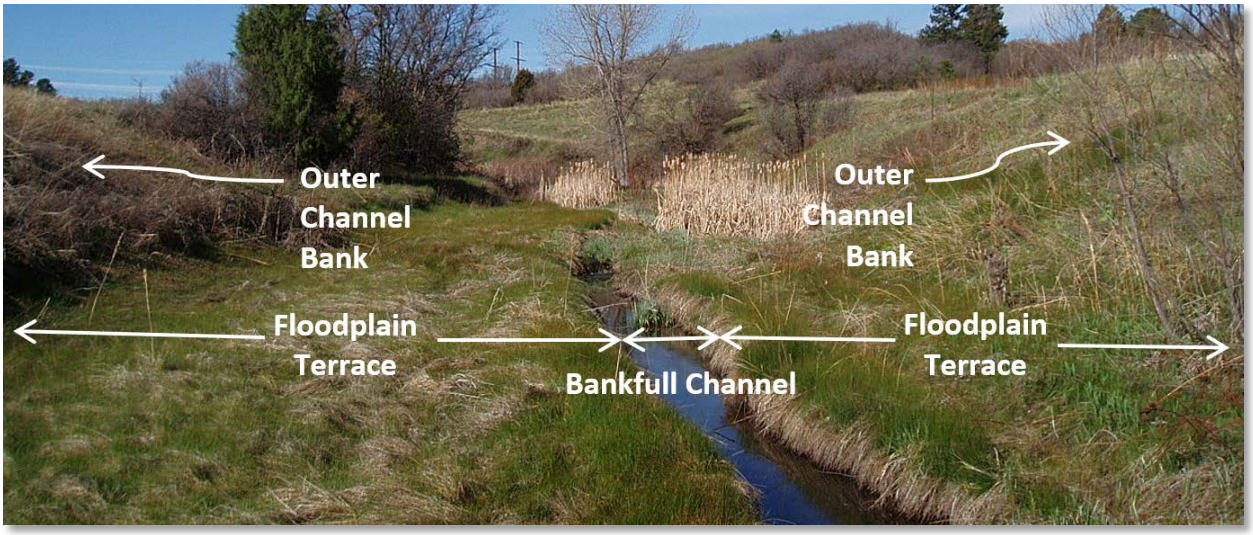


Figure 8-1. Natural channel cross section illustrating floodplain terraces

Natural channels take other forms besides the appearance of the cross section in Figure 8-1. They may be influenced by a relatively high sediment load and have a wide, sandy bankfull channel as illustrated in Figure 8-2. Or they may be vegetated across the entire channel bottom, either with wetland species if the channel is normally wet or transitional or upland species if it is normally dry. Figure 8-3 shows a dry, vegetated stream common to upland areas. These channels also function best when high flows are allowed to spread out over a wider floodplain. Natural steam channels are dynamic and change over time in response to hydrology, watershed conditions, and other factors. Large floods can result in rapid channel evolution/avulsion. When the floodplain is preserved, these natural changes have space to occur with lower potential for damage than channels that are constrained.

During high flow events, the water level rises and spreads to a width and depth associated with a specific return period. Local, State, and Federal floodplain criteria are most commonly associated with the 100-year event. In some cases, the 500-year event is mapped and human development is limited with respect to this criterion. The overall width of the stream corridor should be planned and designed to convey these large flood events that can and will occur.

Figure 8-2. Example sand-bed stream

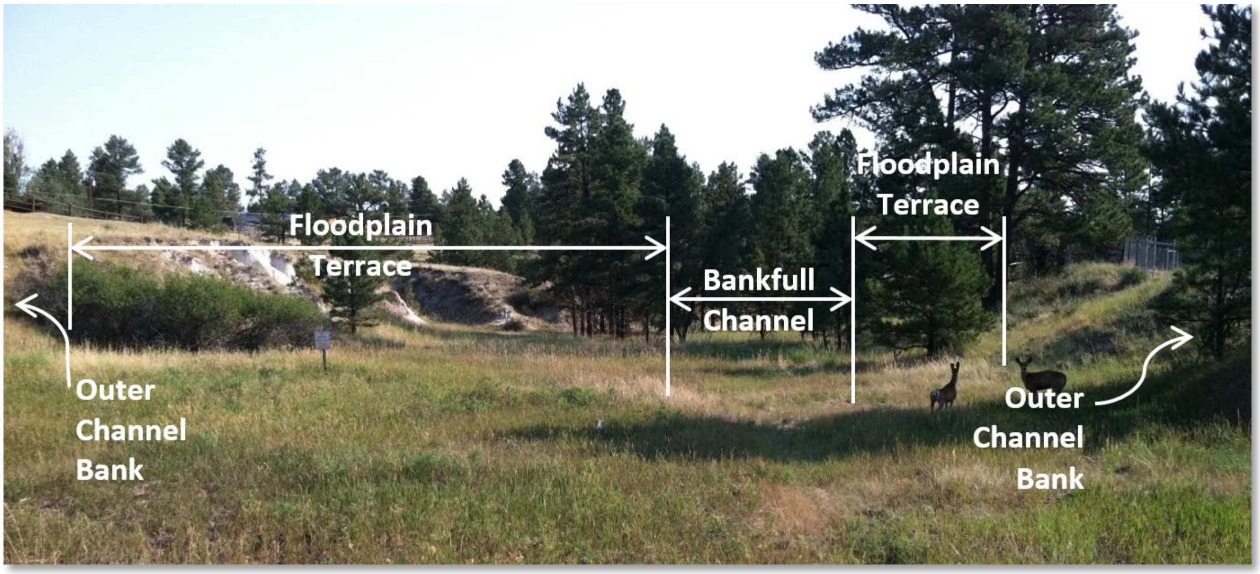


Figure 8-3. Example upland channel

2.1 Functions and benefits of Natural Streams

Healthy streams and floodplains provide a number of important functions and benefits. These are summarized below and illustrated in Figure 8-4.

1. Stable conveyance of baseflows and storm runoff.

2. Support of riparian vegetation.

3. Creation of habitat for wildlife and aquatic species.

4. Appropriate management of energy during a wide range of flows.

5. Promotion of infiltration, groundwater recharge, and exchange of surface and subsurface water in the hyporheic zone located under and adjacent to the low-flow channel (this exchange has been shown to be an important beneficial biological process).

6. Enhancement of water quality through reduced erosion and through vegetative filtering and soil-water interactions.

7. Provision of corridors for trails and open space.

8. Enhancement of property values and quality of life.

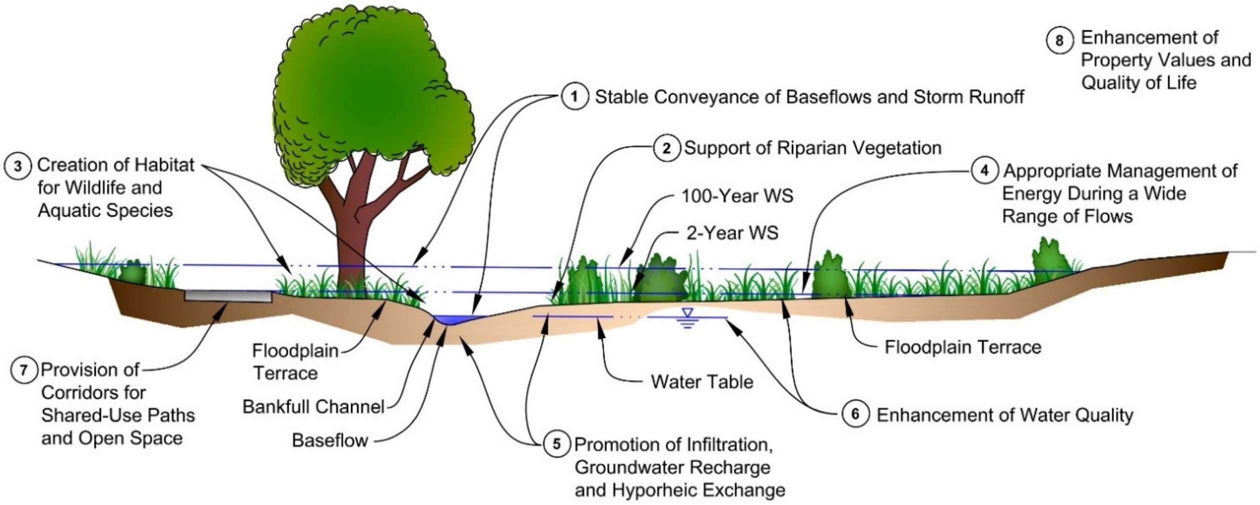


Figure 8-4. Functions and benefits of natural stream corridors (Source: Arapahoe County)

2.2 Natural Stream Corridors Prior to Urbanization

Natural stream systems are dynamic, responding to changes in flow, vegetation, geometry, and sediment supply. In the absence of urbanization, these stream systems are generally free to undergo dynamic change with little negative impact. A free, open, natural stream system is characterized by:

- Space to move and adjust,
- Capacity to convey floods,
- Natural flow regime of water and sediment,
- Channel form adapted to its flow regime, and
- Riparian vegetation established to suit the natural hydrology and soils of the corridor.

Such streams, although subject to aggradation, degradation, and other channel adjustments, are generally able to sustain themselves over the long term.

2.3 Urban Stream Corridors

2.3.1 Impacts and Constraints

In developing urban environments, the driving variables of flow, sediment movement, geometry, and vegetation can undergo significant and rapid changes, exaggerating and accelerating the kind of adjustments the stream makes; as a result, streams in urban environments face threats that can degrade the functions and benefits highlighted in Section 2.1.

In addition, urbanization often places homes, roadways, and infrastructure in close proximity to streams and their floodplains, exposing them to risk of damage from channel movement, bed and bank erosion, and inundation with runoff and mud and debris during flood events. The encroachment of development on stream corridors can limit the allowable width and depth of floodplains, increase velocities and erosive power of flood flows, and impose constraints on the type of improvements necessary to improve channel stability.

2.3.2 Stream Degradation

Urbanization typically increases the frequency, duration, volume, and peak flow rate of stormwater runoff. Based on a review of Colorado Front Range hydrologic analyses, average annual runoff volumes and peak discharges in urban areas can increase by an order of magnitude or more compared to predevelopment conditions. The largest increases in volume and peak discharge occur in the more frequent events that comprise the critical stream-forming flows. In addition, by re-surfacing the ground with pavement and landscaping and installing water quality and flood storage facilities, urbanization can decrease the supply of watershed sediment below pre-development conditions.

Photograph 8-1. Extreme degradation in an unstable channel. (Source: Arapahoe County)

As a result of increased runoff and reduced sediment loading, urban streams tend to degrade and incise toward a flatter slope as the channels seek a new condition of equilibrium to transport that water and sediment. An extreme example of degradation is shown in Photo 8-1. Degradation produces a number of negative impacts to riparian environments and adjacent properties. These are illustrated in Figure 8-5 and described below.

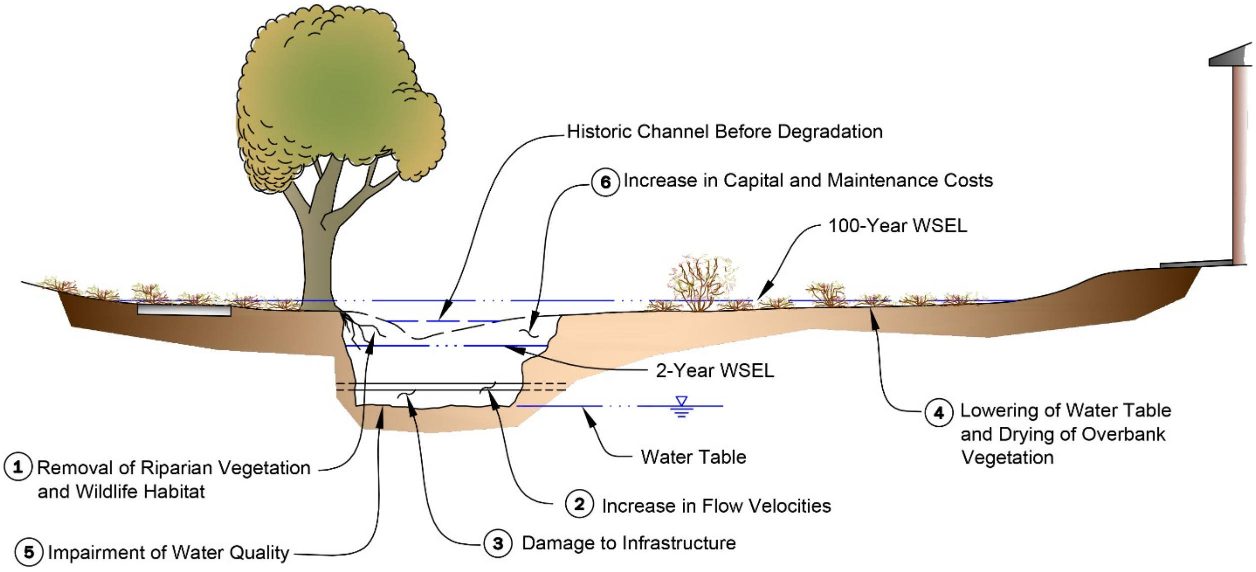


Figure 8-5. Impacts of stream degradation (Source: Arapahoe County)

1. **Removal of Riparian Vegetation and Wildlife Habitat.** Erosion typically strips natural vegetation from the bed and banks of streams. This disrupts habitat for aquatic and terrestrial species and leaves the stream exposed to further erosion damage.

2. **Increase in Flow Velocities.** An incised channel concentrates runoff in a narrow, deep section and increases flow velocities and shear stresses. Increased velocities continue to erode the channel.

3. **Damage to Infrastructure.** Channel erosion can threaten utility lines, bridge abutments, and other infrastructure. Utility pipelines that were originally constructed several feet below the bed of a creek can become exposed as the bed lowers. Damage to the utility lines can result as the force of water and debris come to bear against the line. Channel degradation can expose the foundations of bridge abutments and piers, leading to increased risk of undermining and scour failure during flood events. Erosion and lateral movement of channel banks can cause significant damage to properties adjacent to streams, especially if structures are located in close proximity to the banks.

4. **Lowering of Water Table and Drying of Terrace Vegetation.** In many cases, lowering of the channel thalweg and baseflow elevation leads to a corresponding lowering of the local water table and less frequent flows on the floodplain terraces. Besides the loss of water storage, lowering the water table can "dry-out" the terraces and can effect a transition from wetland and riparian species to weedy and upland species, harming the ecology of floodplain terrace areas. It should be noted that raising the degraded channel up again will raise groundwater levels closer to the surface and may impact properties adjoining the floodplain.

5. **Impairment of Water Quality.** The sediment associated with the erosion of an incised channel can lead to water quality impairment in downstream receiving waters. One mile of channel incision 5-feet deep and 15-feet wide produces almost 15,000-cubic yards of sediment that could be deposited in downstream lakes and stream reaches. Along the Front Range of Colorado, these sediments typically contain naturally occurring phosphorus, a nutrient that can lead to accelerated eutrophication of lakes and reservoirs. Also, channel incision impairs the "cleansing" function that natural floodplain terraces can provide through settling, vegetative filtering, wetland treatment processes, and infiltration.

6. **Increase in Capital and Maintenance Costs.** Typical stabilization projects to repair eroded streams require significant capital and maintenance investment; the more erosion, generally the higher the cost.

Although degraded channels may eventually erode and widen to create new floodplain terraces at a lower elevation following a process called the *channel evolution model* (CEM), this would damage infrastructure and impact water quality in the process. Channel evolution is complex, and a number of different CEMs have been developed by fluvial geomorphologists to conceptually describe how streams typical of the Colorado Front Range evolve (Watson 2002). Instead, stream restoration is encouraged. As discussed in Section 2.2, stream restoration is greatly facilitated if adequate stream corridors are maintained.

3.0 Preserving Natural Stream Corridors

The opportunity to preserve natural stream corridors typically comes only at the outset of planning in a watershed. Preserving natural stream corridors not only preserves valuable habitat and vegetation; it can also reduce impacts and provide for future stream management at a lower cost and smaller footprint compared to constrained floodplains where elevated discharges must be conveyed in narrow corridors.

3.1 Preserve Natural Streams and Riparian Vegetation

As described in Section 2.1, existing natural stream corridors are an important resource offering flood conveyance, desirable riparian vegetation, habitat, landforms, passive recreation, and the potential for water quality filtering and infiltration. Natural stream corridors should be preserved –not filled in, re-graded, re-aligned, or placed in a conduit. Photograph 8-2 shows how development boundaries have been established to preserve a natural stream corridor.

Photograph 8-2. Preserving an existing stream corridor within a developing area.

New construction along streams can produce negative short term effects such as vegetation disturbance, proliferation of weeds, susceptibility to damage during high runoff events, and nutrient leaching associated with runoff coming into contact with freshly disturbed soils. Therefore, it is desirable to preserve as much of a natural stream corridor as possible. If measures are necessary to improve the capacity or stability of a stream reach, it is recommended that these improvements be implemented as "surgically" as possible, preserving valuable land forms, vegetation, and habitat. Photograph 8-3, taken immediately after construction of stream improvements, shows an example of preserving pockets of existing riparian vegetation. Photograph 8-4, taken two years later, illustrates how the overall recovery time of a reach of stream after construction is accelerated by preserving pockets of existing vegetation.

Photograph 8-3. Preserved vegetation during and shortly after construction.

Photograph 8-4. Same channel as left, 2 years after construction.

3.2 Provide Ample Space for Stream and Floodplain

Streams and their floodplains require space to remain fully functional. Ample space needs to be provided both horizontally and vertically.

Horizontal space is necessary to allow the stream to naturally flex and adjust as it seeks dynamic equilibrium. An ample corridor width is necessary to enable high flows to spread out over the floodplain. As is discussed in Section 4.3, relative roughness increases and flow velocity and erosive force decreases as the wetted channel width increases for a given flood discharge. Therefore, wide floodplains are generally more stable than narrow floodplains for a given flow rate.

Ample corridor widths generally allow softer stream improvements more reliant on cross section shaping and vegetation, as indicated in Photograph 8-5. When the available horizontal space is constrained, as shown in Photograph 8-6, channel conveyance and stabilization improvements are always more challenging and costly.

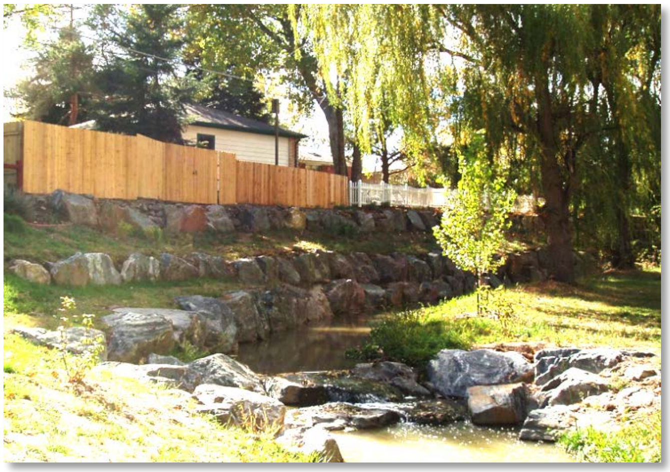
Vertical space is necessary to allow floodplain elevations to rise over time. Floodplain elevations can rise over time due to the following:

- Increased baseflows and runoff from development can promote increased growth of wetland and riparian vegetation, making streams hydraulically rougher and leading to greater flow depths.

Photograph 8-5. Ample space generally allows softer stream improvements more reliant on cross section shaping and vegetation.

- Stream restoration work usually has the goal of raising the bed of incised channels to levels that existed prior to degradation. This effort, plus modifying channel slopes to flatter or more stable grades, can increase water surface elevations above mapped or regulatory floodplains modeled based on the degraded condition.

- Upstream bank erosion or watershed erosion over time can lead to sediment deposition and channel aggradation in downstream channel reaches that may have wider sections, flatter slopes, or increased channel vegetation–raising streambed and floodplain elevations.



Photograph 8-6. Channel improvements tend to be more structural and costly when space is limited.

The most important reason for providing ample space for streams is recognizing the tremendous power of floods to convey and deposit rock, mud, and debris and carve new channel alignments irrespective of property or infrastructure. The Front Range floods of September 2013 showed that impacts are often felt beyond the limits of regulatory floodplains. As an example, Figure 8-6 indicates that the area impacted by the 2013 flood (indicated by blue shading) in this reach of Fourmile Canyon Creek in Boulder is larger than the area of the regulatory 100-year floodplain (indicated by red outline), even though the 2013 event was estimated to have a peak discharge less than the 100-year flow rate.

Therefore, providing ample space for streams in the following ways is strongly recommended to reduce risk to people and property.

Figure 8-6. Fourmile Canyon Creek, September 2013 flood impacts and floodplain

Avoid Floodplain Filling and Encourage Stream Preservation Zones. Building structures adjacent to floodplains carries risk; filling existing floodplains and building structures closer to flooding sources increases that risk, especially when the filling creates higher flood velocities. Some communities have adopted stream preservation zones that limit filling and new development within stream corridors that may be wider than the 100-year floodplain. This is prudent given the power and unpredictable nature of floods. Support for this policy can often be seen in aerial imagery as shown in Figure 8-7. The historic meander belt width, indicating channel movement over time, can be many times wider than regulatory floodplains.

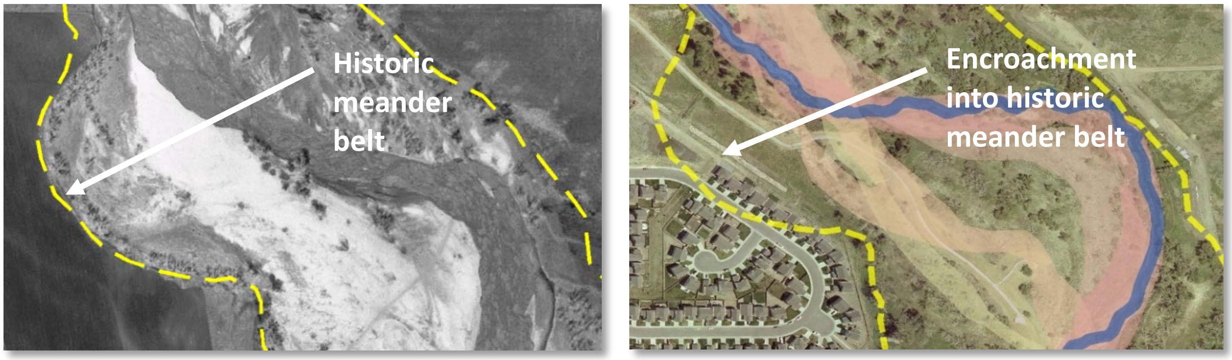


Figure 8-7. Importance of stream preservation zones

Provide Ample Freeboard. Freeboard is the vertical distance above a referenced floodplain water surface to a specific elevation associated with constructed infrastructure, typically the lowest elevation of a building site adjacent to a floodplain, the lowest habitable floor of a structure, or the low chord of a bridge spanning a stream. It is critical to recognize that higher water surface elevations can and will occur as a result of increased channel vegetation and roughness, aggradation, raising degraded inverts, and flood debris. Urban Drainage and Flood Control District (UDFCD) recommends providing 18 inches or more of freeboard for new development projects to account for these changes, as these changes cannot be considered when determining the regulatory floodplain. Bridges often have higher freeboard requirements to account for debris. Where risk or damage associated with flooding is high, or there is high potential for sediment, rocks, and debris in runoff, the designer should elect to incorporate additional freeboard.

3.3 Manage Increased Urban Runoff

Stream degradation is often associated with the increased peak discharge, volume, and frequency of urban runoff, especially during small (occurring multiple times each year) to moderate (occurring once every several years) flood events. Employing runoff reduction techniques (e.g., minimizing directly connected impervious areas) as well as implementing full spectrum detention to reduce urban runoff peak flows and volumes can mitigate the impacts of urbanization. These two strategies represent Steps 1 and 2 of the Four Step Process as described in Volume 3 of the Urban Storm Drainage Criteria Manual (USDCM).

Runoff reduction can be accomplished through a variety of techniques, including the following, each of which is described in Volume 3:

- Minimizing directly connected impervious area,
- Grass buffers and swales,
- Permeable pavements,
- Bioretention/rain gardens, and
- Sand filters.

Full spectrum detention, if implemented in significant portions of a watershed, holds the potential for controlling peak discharges to levels similar to pre-development conditions over a wide range of storms from small, frequent events to large, rare events. If portions of a watershed have been developed without full spectrum detention, or without any detention at all, local governments may be able to explore opportunities to retrofit full spectrum detention facilities to reduce the impacts of elevated urban runoff.

Master plan modeling has shown that retrofitting regional full spectrum detention in a watershed can more than pay for itself in reduced stream stabilization costs (Cottonwood Creek Outfall Systems Plan, 2012 and Happy Canyon Major Drainageway Plan, 2014). Full spectrum detention is described in detail in the *Storage* Chapter of Volume 2.

It is generally good practice to locate regional detention facilities on smaller tributaries with low sediment loading rather than in streams having significant upstream watershed area and sediment load. This reduces the likelihood that the detention facilities will quickly fill with sediment from the natural stream system and release flows with reduced sediment load that may initiate a cycle of degradation in the reach downstream.

However, siting a regional detention facility on a larger stream where the sediment load is low, the upstream and downstream reaches have low erosion potential, and where regional water quality is a specific objective may be beneficial. Several of these large online regional detention facilities have been constructed on streams leading into Cherry Creek Reservoir in Denver as part of an overall plan to protect water quality in the reservoir.

3.4 Monitor and Proactively Address Channel Instability

The restoration process is intended to be proactive, best started prior to the onset of significant development and resulting stream erosion in the watershed. Addressing problems when they are small rather than waiting until severe degradation occurs reduces disturbance to existing vegetation and habitat resources, protects water quality, and reduces the extent and cost of stabilization improvements. The objective of a proactive stream stabilization approach is to implement improvements at the appropriate pace, in the appropriate locations, and of the appropriate type to stay ahead of problems.

A proactive approach to address channel instability requires a commitment to undertake regular surveys of stream systems, identify early signs of degradation, aggradation, earmark funding, secure easements, and undertake design and construction of improvements at a relatively early stage in the erosion process. A proactive approach generally allows a set of improvements that is relatively modest, soft, oriented toward reinforcing potential weak points, and intended to work in conjunction with the portions of the existing stream system that are generally stable on their own. This reduces the extensive disturbance, re-grading, and structural measures that are often necessary to address severe erosion after it has already taken place. Proactive measures can be financially challenging as these need to be constructed prior to development; however, the alternative of waiting until the channel degrades is more costly.

Photograph 8-8. Proactive stabilization at McMurdo Gulch, constructed with little disturbance to the existing channel.

4.0 Stream Restoration Principles

This section introduces the concept of stream restoration. In general, stream restoration is aimed at re-establishing the natural and beneficial functions of a stream corridor depicted in Figure 8-4. Although a degraded channel similar to the condition shown in Figure 8-5 and Photograph 8-7 could be left in a narrow, deep configuration and perhaps protected with heavy rock lining, stabilizing the invert in its lowered condition would potentially perpetuate a low water table, dried out terrace vegetation, high flood velocities, and reduced water quality filtering and infiltration in the terraces. It would be ideal, and often less expensive, to raise the invert to re-connect the channel with its floodplain, as shown in Photograph 8-8. It is better to promote healthy floodplain terrace conditions that can handle periodic flood flows, controlling increased runoff from development than to "force" a degraded channel into a stabilized condition using extensive structural measures.

Photograph 8-7. Degraded channel (before restoration).

Photograph 8-8. Same channel as photo 8-7 after restoration.

Eight principles for stream restoration are discussed in the following subsections. The principles are valid for a variety of stream conditions, whether the corridor has been preserved and protected as described in Section 3.0 or constrained and impacted through urbanization. Special design considerations are recommended for constrained urban stream reaches where velocities and shear stress imposed by elevated peak discharges are greater and infrastructure tends to be in close proximity to the stream. Stream restoration measures tend to be more structural and costly in constrained corridors where maintaining or increasing flood capacity is typically the highest priority.

The principles are not a "cookbook" or "one size fits all" set of design steps, but rather principles to be applied to channel reaches with the experience, judgment and collaboration of a multi-disciplinary design team. Consider the following expertise when developing the design team: surface and subsurface hydrology, hydraulics, geomorphology, plant ecology, terrestrial and aquatic biology, environmental permitting, landscape architecture, geotechnical, and water rights.

What does *Restoration* mean?

Stream restoration is the process of assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the natural system (Bledsoe, 2013).

Restoration is the manipulation of the physical, chemical, or biological characteristics of a site with the goal of returning natural/historic functions to a former or degraded aquatic resource (Corps of Engineers, 2011).

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Society of Ecological Restoration, 2004).

Restoration refers to actions that result in the re-establishment of ecological processes, function, and biotic/abiotic linkages, that lead to a persistent, resilient ecosystem that is integrated within its landscape (Society of Wetland Scientists, 1998)

From the definitions above, the idea is communicated that restoration is a matter of *assisting* ecosystems that are in a *degraded* condition to re-establish *healthy processes and functions*. Although other terms, such as reclamation, rehabilitation, and stabilization, may be used to describe activities improving the structure and health of stream corridors, especially in urban or disturbed environments, the term “stream restoration” will be used in this chapter.

4.1 Understand Existing Stream and Watershed Conditions

Before any design work on a stream reach takes place, it is imperative to understand the existing conditions associated with the stream and its watershed. Review the current master plan including upstream and downstream reaches and major tributaries flowing into the reach. The master plan also provides information on existing and future development, allowing for an understanding of potential impacts due to anticipated growth. Understanding development plans and planning/zoning documents is an important component to understanding watershed conditions. Comprehensive field reconnaissance should also be performed. The following types of information should be observed on a reach by reach basis:

- Planform geometry, such as the information illustrated in Figure 8-8. Further discussion regarding channel sinuosity can be found in Section 4.4.
- Cross-section geometry, especially width and depth of the main channel below adjacent terraces, relative elevations and widths of terraces, heights and slopes of channel banks.
- Bankfull width and depth and the channel entrenchment ratio as defined in Section 4.3.
- Stream bed conditions, including bed material type and particle size, riffle characteristics, pools, steps, rock outcrops, presence of baseflows, and indications of the amount of sediment transport.
- Longitudinal slope of channel and valley along their respective centerline alignments.
- Vegetation characteristics along the channel, in floodplain terraces, at knickpoints, and channel banks.
- Signs of instability (e.g., headcuts, bed degradation/ aggradation, bank erosion, constricted channel sections) and stability (e.g., lack of erosion, favorable cross sectional geometry, dense vegetation).
- Existing facilities that modify hydrology and hydraulics such as dams, wastewater treatment plants, ponds, detention facilities, storm drain outfalls, or grade control structures.

- Horizontal distance from stream and elevation above stream of any structures or development parcels adjacent to stream as well as total unencumbered width of floodplain.
- Locations of infrastructure such as roadway crossings and utilities.

Figure 8-8. Planform geometry of a meandering river system

A reference reach (a stream reach with similar hydrology and watershed characteristics that displays characteristics of a stability without artificial means) can be used as a template for design of a stream restoration project. Although suitable reference reaches rarely exist for urban streams, when a reference reach can be identified in a relatively undisturbed and healthy portion of the stream or a similar stream, characteristics of a the reach can often serve as a guide for creating similar characteristics in an impaired reach.

Additional information regarding field data to collect for assessment is provided in *A View of the River* (Leopold 1994). Existing conditions should be documented with field notes, photos, and quantitative comparisons of measurable parameters.

Any available historic aerial photography should be carefully reviewed and compared to current channel conditions, noting changes that have occurred over time, and especially after large flood events. Interviews with nearby residents are another means of gathering information on the history of streams.

Available information on regulatory flow rates and floodplains and gage data should be obtained and reviewed, along with master plans and any prior stream stabilization. It is important to assess how much flows have increased from predevelopment conditions to current levels and how much further they may increase with future development–for large floods like the 100-year event and also for more frequently occurring floods such as the 2-year event. This comparison will help to quantify the increased velocities and shear stresses imposed on the stream over a range of flow rates and will help to guide the design of stabilization measures.

Assess not only the stream but also the watershed. Evaluate current aerial photography of the watershed to understand the locations and densities of existing developments. Obtain planning documents and development plans that show projected land use to estimate the extents, representative imperviousness, and anticipated timing of development projects in the watershed. The larger the development, higher the average imperviousness, and quicker the anticipated build-out, the more the potential impact on downstream channels. Review information on soils, imperviousness, hydrology, hydraulics, detention facilities, and improvement recommendations in any existing master plans conducted for the watershed.

By understanding channel behavior historically, currently, and projected into the future, the designer will have the foundation needed to develop strategies for improving the stability of the stream.

Stream Restoration Principle 1: Understand Existing Stream and Watershed Conditions

Representative Design Tasks and Deliverables

1. Document results of field observations and background research on project reach, applicable reference reaches, and watershed.
2. Compile representative photos along reach.
3. Compare future development design flows for return periods ranging from 2-year to 100-year to existing and, if available, pre-development conditions to assess the relative increase in stresses imposed on the project reach.
4. Summarize findings as they apply to the design of improvements in project reach.

4.2 Apply Fluvial Geomorphology Principles to Manage Sediment Balance

A drainage system within a watershed involves flowing water, described by the term *fluvial*. *Geomorphology* is the study of landforms and the processes that influence the shape and dynamics of landforms. The flow of water and the associated movement of sediment that forms and shapes streams are processes that are identified as *fluvial geomorphology*. Surface form characteristics of stream channels behave in a dynamic and 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 from the stream bed and banks and supplied to the channel. The sediments eroded, moved by the flowing water, and deposited in turn influence channel hydraulic characteristics.

4.2.1 Aggradation, Degradation, and Equilibrium

An alluvial channel is usually considered stable and in equilibrium if it has adjusted its width, depth, slope, and other factors so that the channel neither aggrades nor degrades, resulting in no significant change in channel cross section over time. This is a dynamic equilibrium in which the sediment supply from upstream is generally equal to, or in balance with, the sediment transport capacity of the channel for the full range of flows. Under watershed conditions with normal hydrologic variations affecting runoff and sediment inflow, this balance shifts and some adjustments in channel characteristics are inevitable.

An illustration, shown as Figure 8-9 (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:

$$Q_w S \propto Q_s D_{50} \qquad \text{Equation 8-1}$$

Where:

Q_w = water discharge

S = channel slope

Q_s = bed material load

D_{50} = mean particle size of bed material

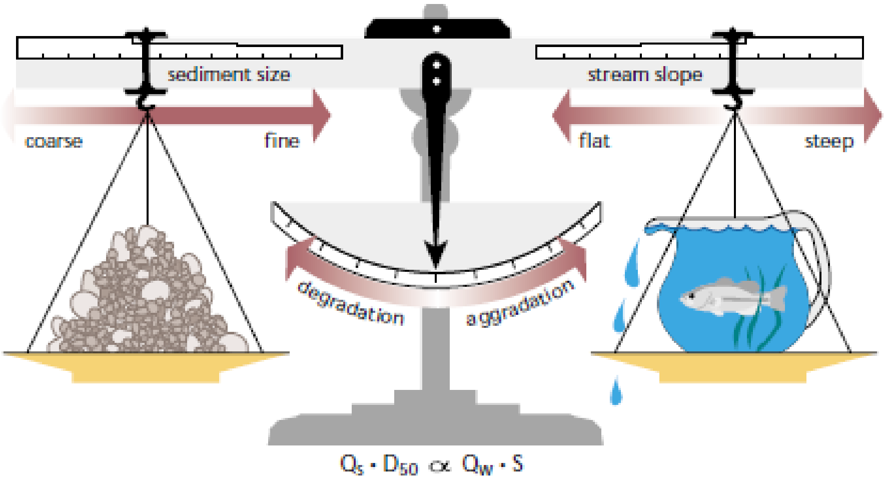


Figure 8-9. Lane's diagram

For a stable channel, these four parameters are balanced, and, when one or more of the parameters changes, the others adjust over time to restore the state of equilibrium. For example, a typical response to increased flow associated with urbanization is an increase in bed material load through erosion of the channel and a corresponding reduction in slope. This describes channel degradation that is prevalent in urban streams. Preserving natural stream corridors and reducing urban runoff as described in Section 3.0 will reduce the magnitude and progression of stream erosion and associated deposition; however, degradation and aggradation will still occur to some extent in preserved stream corridors. Degradation and aggradation tends to be more pronounced in urban streams.

Photograph 8-9. Degradation in a channel.

The presence of channel degradation (erosion) or aggradation (sedimentation) is readily identified in the field. Degradation is evidenced by lowered channel inverts, high eroded channel banks, flatter longitudinal slopes, and other impacts illustrated in Figure 8-5 and Photograph 8-9. On the other hand, aggradation appears as mud, sand, or coarser sediment accumulated on the bed or floodplain terraces of a stream, burial of lower stalks of herbaceous or woody vegetation (see Photograph 8-10), steeper longitudinal slopes, and often a relatively shallow and sometimes wide sandy active channel. Aggradation and degradation processes may differ between the active channel and adjacent terraces. Sediment deposition can occur on densely vegetated terraces at the same time that degradation occurs in the active channel.

Photograph 8-10. Signs of aggradation include fresh, sandy deposition and the burial of plant stems.

Evidence of aggradation and degradation over time can be documented by comparing current survey information of the stream invert to any prior survey or mapping information or bed elevations that may be indicated in past floodplain or master plan profiles, considering any datum differences. For large streams, bridge maintenance records often record streambed elevations over time and original bridge design plans may indicate streambed elevations at the time the bridge was constructed. Plotting the current streambed profile against prior information is a good way of illustrating degradation and aggradation.

It is not unusual to find aggrading reaches downstream of severely degrading reaches as the high sediment load generated by the degrading reach finds a lower-energy reach and drops out. The clearer water downstream of the aggrading reach often begins another reach of degradation and the conditions can repeat in alternating cycles along the length of a stream. Although the aggrading reaches downstream of degrading reaches may appear stable, their stability may be dependent on the abnormally high erosion rates upstream; if the degrading reaches are stabilized, reaches that were formerly aggrading or in a quasi-stable condition may begin to degrade.

It is the designer's responsibility to understand aggradational and degradational conditions along a stream and develop improvement plans that intend to appropriately manage the sediment balance.

4.2.2 Dynamic Equilibrium and Threshold Principles in Stream Restoration

In its purest form, a dynamic *equilibrium* approach to stream restoration seeks to re-establish a horizontal and vertical configuration of a stream–encompassing cross section shape, longitudinal slope, sinuosity, meander pattern, bed material, and terrace vegetation that will convey inflowing sediment and sustain itself in dynamic equilibrium over a range of flow conditions without the use of hard structures. This is not to say that there will not be degradation and/or aggradation from event to event; however, over the long-term the degradation and aggradation are balanced. Equilibrium approaches have been successfully implemented by experienced practitioners to restore the health of natural stream systems, especially in montane and non-urban environments. The dynamic equilibrium approach can be very challenging in a continuously-urbanizing watershed with non-cohesive soils.

A *threshold* approach, in contrast, relies on rock or hard structures for grade control or bank protection that are sized to remain in place for a given range of design flow rates. As long as the design hydraulic threshold is not exceeded, the structures are designed to remain in place. Threshold techniques can be applied to the vegetative cover in floodplain terrace areas as long as shear stresses imposed by the design flow do not exceed the resistive stress strength of the vegetation and soil. Threshold approaches have also been successfully implemented to restore impaired stream systems, especially in the urban environment.

Pure equilibrium approaches are most feasible when the following factors exist:

1. Open, unconstrained stream corridors (to allow dynamic adjustments and enable flows to spread over floodplain to dissipate energy), with gentle valley slopes.
2. Natural hydrology relatively unaffected by urban impacts (to reduce imbalances caused by flow regime).
3. Significant sediment supply (the "building material" necessary to form the stream).
4. Relatively consistent, predictable sediment supply for given flow range (to sustain the stream form over time).
5. Cobble or gravel-bed streams (compared to sand-bed streams, are better able to resist erosion, maintain steeper slopes, promote armoring, and help form natural riffles to assist with grade control).

Stream Restoration Principle 2: Apply Fluvial Geomorphology Principles to Manage Sediment Balance

<u>Representative Design Tasks and Deliverables</u>

1. Plot current streambed profile of project reach and upstream and downstream reaches against available information showing prior streambed elevations to estimate relative aggradation and degradation.
2. Document geomorphic assessment of stream addressing sediment supply, evidence of degradation and aggradation, predictions of future trends, and any quantitative analyses of sediment supply and equilibrium.
3. Indicate how findings of geomorphic assessment are to be applied to the design of stream restoration improvements in the project reach.

Factors 1 and 2 are characteristic of protected natural stream corridors as described in Section 3.0; therefore, equilibrium approaches are most feasible in protected corridors that also demonstrate one or more of the other three factors. The more a stream is constrained and impacted by urbanization, the more challenging it is to implement a pure equilibrium approach to stream restoration. As mentioned, successful implementation of a pure equilibrium approach requires a high level of understanding and experience in fluvial geomorphology principles.

A number of references have been published on the subject (Rosgen, 1996, USACE (Copeland et al), 2001, USACE (Soar and Thorne) 2001). Threshold approaches have been more often used for stream restoration in urban environments. Threshold approaches are somewhat more predictable and can be used when conditions favorable to equilibrium approaches (identified above) do not exist. Threshold approaches can be designed in several ways. In its most extensive form, it can consist of lining the entire stream width and length with rock sized to not move in the design event. More often, the threshold structures are comprised of vegetated bank protection and regularly spaced grade control structures constructed of sculpted concrete, grouted or loose boulders, and/or riprap.

In effect, most stream restoration projects in the urban environment use a hybrid approach. Threshold principles are employed for grade control structures and equilibrium principles can be used in the soft stream reaches between drop structures.

4.2.3 Support the Stream's Natural Capacity to Sustain Itself

Sustainability

The goal is not to "build" natural habitat and fully completed streams, but to assist in creating the conditions where the system can strengthen and maintain itself.

If the fluvial geomorphology principles discussed above are understood, the restoration process itself can be oriented toward creating a healthy channel configuration and thus assisting the stream system in sustaining its functions primarily on its own. Natural stream systems can act like living entities, responding and adapting to try to maintain balance. The flow of water and sediment, the establishment of riparian vegetation, and the biologic processes in streams and floodplains all have the potential to sustain themselves within a dynamic envelope over a long period of time. In a word, streams systems have a capacity for *resilience*.

The key is to protect streams from major impacts, such as severe channel incision with potential to degrade the system to a point that it cannot recover on its own, and to allow the stream enough space for some degree of natural response. The floods of September 2013 provided multiple examples where streams that had been straightened or narrowed either found their historic alignment or created a new alignment all together. Floods usually serve to remind us that streams are difficult to control if their space requirements are not understood.

The restoration approach is successful if the passage of time results in the stream system getting stronger and healthier through the working of natural stream processes, rather than weakening and degrading over time. The goal is not to "build" natural habitat and fully completed streams, but to assist in creating the conditions where the system can strengthen and maintain itself.

4.3 Establish Effective Cross-Sectional Shape

One of the most fundamental principles in stream restoration is establishing an effective cross-sectional shape. This section describes the importance of a favorable cross-section shape to maintaining the function of a floodplain, discusses “bankfull” channel sizing, and illustrates how cross-section shape influences flow velocities and shear stresses.

4.3.1 Maintaining Floodplain Function

A primary design task is to preserve or establish a floodplain cross section that maintains the natural function of a floodplain–a section with a bankfull channel that is appropriately sized to allow flood flows to spread out over vegetated floodplain terraces for stable conveyance, vegetative filtering, infiltration, and energy dissipation. The bankfull channel should be shallow enough to maintain a connection to the floodplain. In some reaches, deeper areas for aquatic life should also be considered. Severely degraded, incised channels do not allow that connection.

Figure 8-10 illustrates the influence of cross-sectional shape. The figure consists of three cross sections carrying the same flow rate with varying flow characteristics. The first section represents a degraded, incised channel whose flow area fills the incised channel just below the point where it would spill into the adjacent floodplain. The second section is the same as the first except that the active channel was filled to hydraulically reconnect the floodplain. It has a depth of 1.5 feet below the floodplain terraces. The third section has the same size active channel as the second, but a wider and shallower floodplain terrace.

The sections show a color-coded velocity distribution of each section. Average flow velocity in the active channel and terraces in feet per second are indicated, showing how velocity decreases as the section gets wider and shallower. Therefore, unless excessive sedimentation is expected, establishing stream configurations with relatively shallow bankfull channels and wide floodplain terraces are encouraged, since they are inherently less erosive than deeper, narrower sections. The size of the bankfull section is the most critical aspect of the cross-section in maintaining floodplain function and should be sized appropriately considering all geomorphic principles provided in this chapter.

Connecting the Floodplain

The bankfull channel should be shallow enough to maintain a connection to the floodplain and provide occasional flooding of the riparian vegetation.

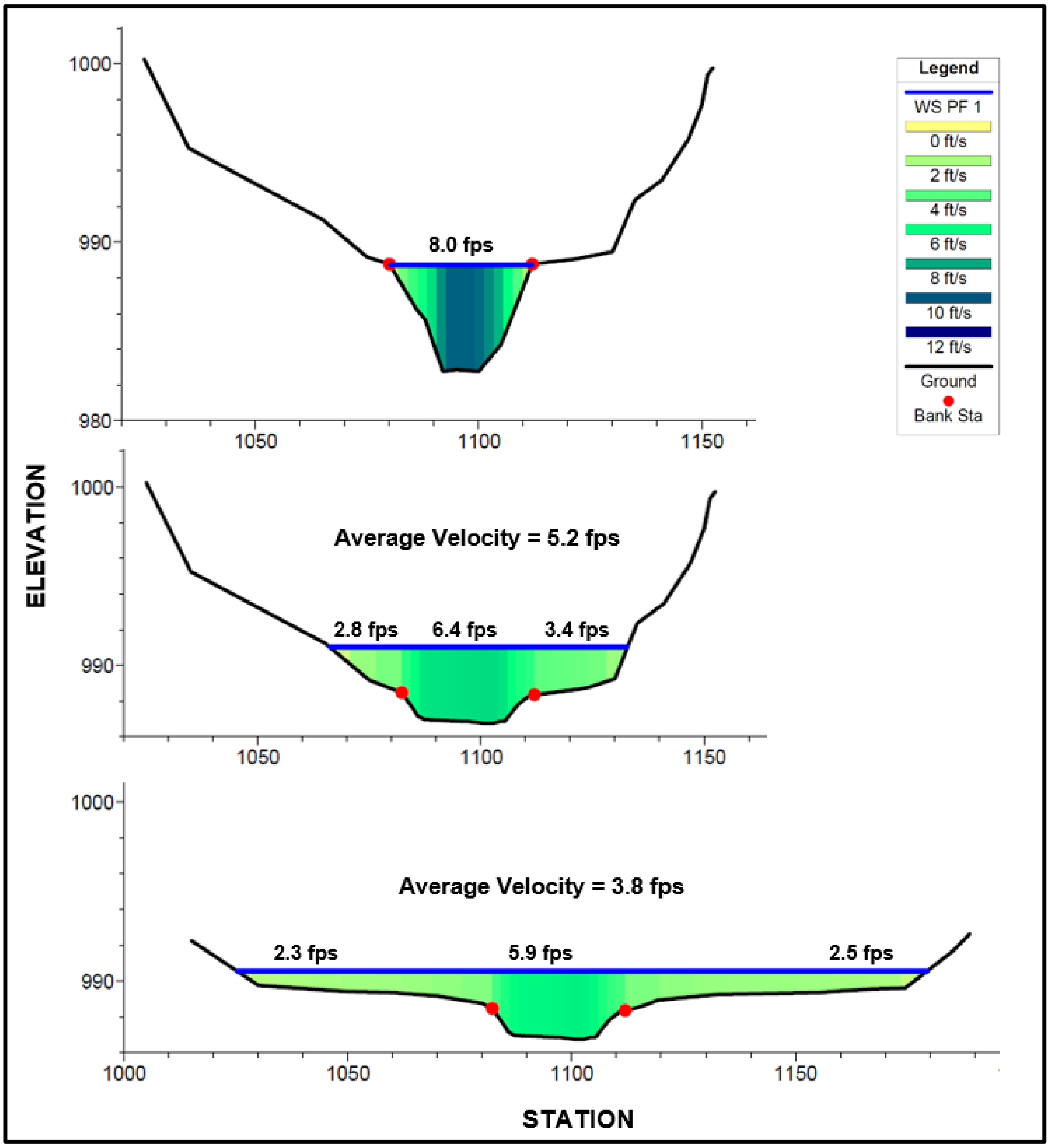


Figure 8-10. Impact of channel geometry on velocity

4.3.2 Sizing of Bankfull Channel

Bankfull channels were introduced in Section 2.0 and indicated in Figures 8-1 through 8-4. Based on geomorphic principles, appropriate sizing of the bankfull channel can be related to a particular discharge, termed "bankfull discharge." Bankfull discharge is defined as the discharge where flow is just about to spill out into its floodplain terraces. Bankfull discharge is further illustrated in Figure 8-11. This section provides several approaches to approximate the appropriate bankfull discharge and in turn, determine the appropriate sizing for the bankfull channel.

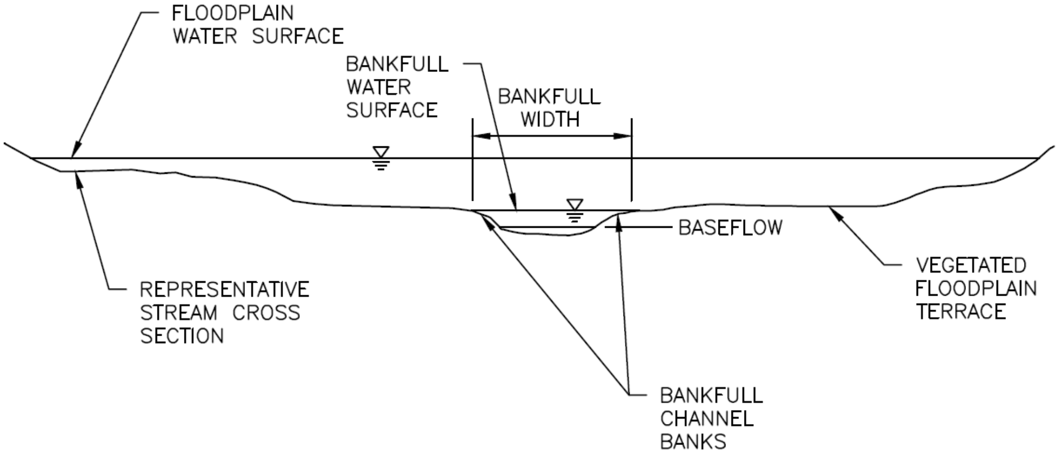


Figure 8-11. Channel cross section with bankfull discharge illustration

Based on reference reach. If stable, the width and depth of the bankfull channel of a reference reach is a good starting place to estimate bankfull channel dimensions in the design reach, assuming the reference reach has not already been altered by past channelization projects. The associated bankfull discharge may be estimated based on bankfull capacity of stable alluvial reference reaches upstream or downstream of the design reach. The process involves observing the depth at which flows just spread out into adjacent floodplain terraces and then estimating the capacity of the bankfull channel at that depth based on the actual slope, roughness, and cross sectional area.

Based on return period. Bankfull channels are not formed based on a single return period event, however; bankfull discharge in stable natural channels has sometimes been observed to be between the 1.5- to 2-year event (Leopold 1994). In urban settings where other methods for sizing the bankfull channel may not be practical, UDFCD recommends using a bankfull discharge value equal to the developed 1.5 to 2-year flow when sizing the bankfull channel. Determination of the 1.5 to 2-year flow should be based on gage records, when available, although the resulting flow estimates will represent the development conditions existing during the period of record and may need to be adjusted upward to account for higher projections of future imperviousness. If the 1.5 to 2-year flow is based on the results of a hydrologic model, caution should be applied since variables such as floodplain infiltration can reduce observed stream flows and result in overly inflated modeled flows for frequent events, especially in large watersheds.

Based on effective discharge. Effective discharge is defined as the discharge that transports the largest percentage of the sediment load over a period of many years. It is used synonymously with “channel-forming” or “dominant” discharge, a theoretical discharge that, if maintained indefinitely, would produce the same channel

References for Determining Bankfull Discharge

The following link directs readers to a video providing guidance for field identification of bankfull stage in the western U.S.:

http://www.stream.fs.fed.us/publications/bankfull_west.html

Chapter 5 of *Applied River Morphology* (Rosgen, 1996) describes bankfull discharge, stage, and field determination of bankfull conditions.

Leopold, 1994 also provides guidance on determining bankfull depth in the field.

geometry as the natural long-term hydrograph. Quantitative analyses to determine effective discharge are fairly complex and depend on good data and proper application of assumptions and methods. Effective discharge analyses are documented in *Hydraulic Design of Stream Restoration Projects* (USACE 2001) and other geomorphology references. Using the effective discharge to size the bankfull channel implies an assumption that an appropriately sized bankfull channel could be based on the effective discharge, (i.e., the bankfull discharge and effective discharge are assumed to be equal).

Regardless of how the bankfull discharge is estimated, geomorphic relationships make it possible to use this value to help determine appropriate sizing of the bankfull channel width and depth. The width for natural alluvial streams has been related to bankfull discharge according to the following equation (Leopold 1994):

$$w = aQ^{0.5}$$ Equation 8-2

Where:

w = bankfull width of channel (top width when conveying bankfull discharge)

Q = bankfull discharge

a = 2.7 (wide bankfull channel)
  2.1 (average bankfull channel width)
  1.5 (narrow bankfull channel)

Although this relationship applies to natural alluvial steam systems, it may serve as an approximation for streams in an urban environment, especially if corroborated with reference reach dimensions in streams not already altered by past channelization projects.

In addition, the width/depth ratio, defined below, is a useful parameter that can be key to understanding the distribution of energy within the channel and the ability of the channel to move sediment (Rosgen 1996).

$$\frac{\text{Width}}{\text{Depth}} = \frac{\text{W}}{\text{D}} = \frac{\text{bankfull channel width}}{\text{mean depth of the bankfull channel}}$$ Equation 8-3

Based on the relationship between bankfull width and bankfull discharge described by Equation 8-2, it is possible to estimate bankfull width based on bankfull discharge and then select a bankfull channel depth based on the area of conveyance needed to contain the bankfull discharge.

This exercise translates into width to depth ratios generally in the range of 6 to 16. Typical bankfull channel depths range from about one to three feet, where the later would be typical for bankfull channels that are a minimum of 18 feet wide. This typical width to depth ratio range of 6 to 16 appears to be generally representative of healthy streams within the UDFCD area. Streams in semi-arid areas tend to have a high width to depth ratio.

4.3.3 Addressing Incised Channels

Degraded streams that are too deep may require filling of incised channels, excavating floodplain terraces adjacent to the bankfull channel, or some combination of the two. Usually, filling a degraded channel is the option that results in the least disturbance to existing floodplain vegetation.

It is sometimes difficult to raise the invert of a degraded channel due to costs associated with importing fill material (if it cannot be generated onsite) or existing infrastructure such as storm sewer outfalls located near the bottom of the incised channel. It may be necessary to remove the downstream end of low storm sewer outfalls and reconstruct them at a higher elevation. Raising the invert will also cause a rise in a critical floodplain elevation if the regulatory floodplain was based on the degraded channel condition (as discussed in Section 3.2, it is recommended that floodplains be determined for restored, not degraded channel conditions). There may be a need for compensatory excavation in another portion of the floodplain to offset any rise in the floodplain caused by filling in the eroded active channel.

4.3.4 Floodplain Terraces

As discussed above, the existence of floodplain terraces immediately above and adjacent to the bankfull channel help to spread and dissipate the energy associated with high flows. Floodplain terraces may exist on one or both sides of the bankfull channel.

It is desirable that floodplain terraces adjacent to the bankfull channel be relatively wide, flat, well-vegetated, and not excessively steep with respect to longitudinal slope. Terraces with these characteristics assist with reducing flow velocities and provide adequate capacity for larger storm events. Generally speaking, the wider the floodplain terraces, the lower the flow depths for a given return period event, the greater the relative roughness, and the lower the velocities of flow, as shown in Figure 8-10.

A useful parameter for quantifying the width of the floodplain terraces in streams not already altered by past channelization projects is entrenchment ratio, which should be similar to those of stable upstream or downstream reference reaches, ideally in the range of about three or greater. The entrenchment ratio, defined below, provides a measure related to the distribution of shear stress and the potential for erosion within the channel section (Rosgen 1996):

$$\text{Entrenchment Ratio} = \frac{\text{flood prone channel width}}{\text{bankfull channel width}} \qquad \text{Equation 8-4}$$

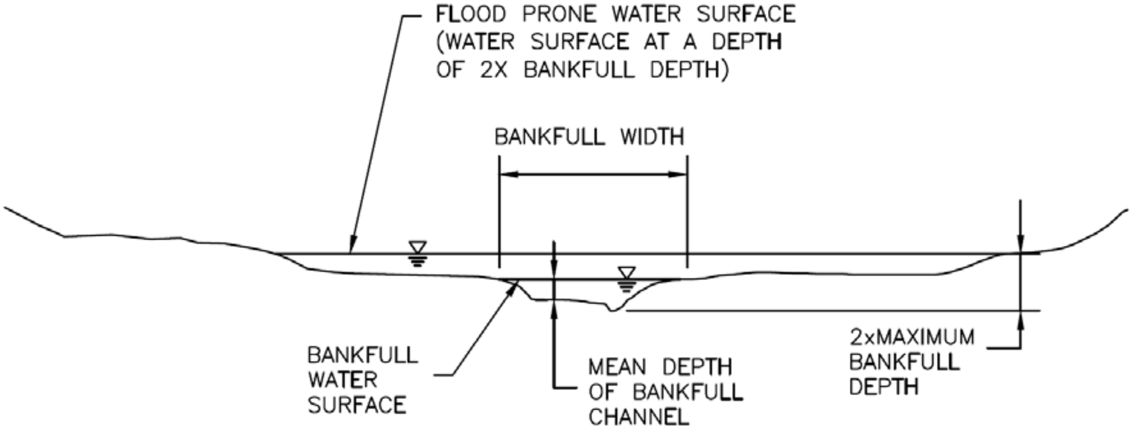
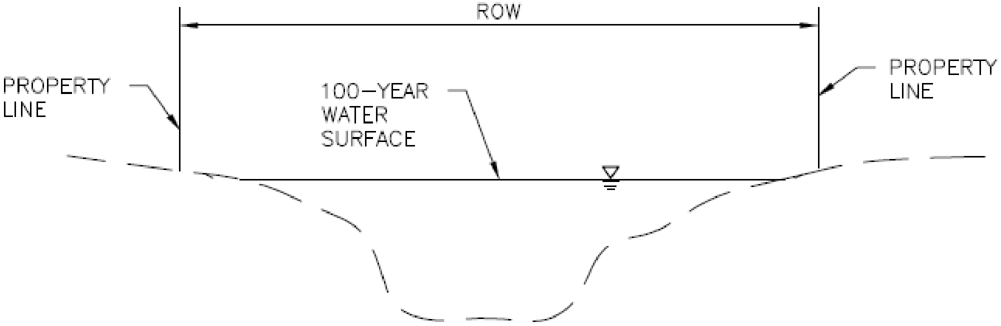


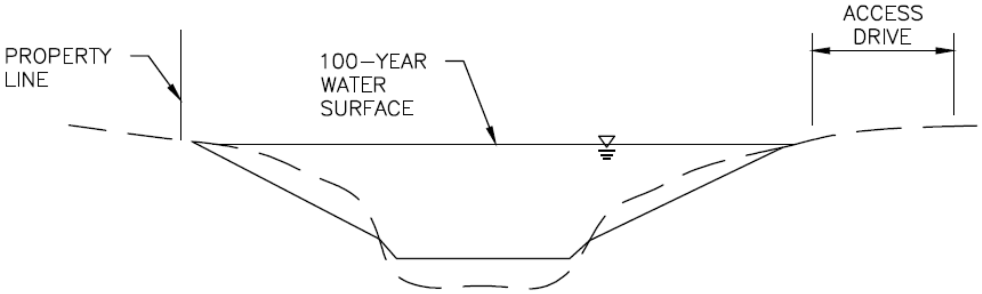
Figure 8-12. Channel cross section with bankfull and flood prone water surfaces (Rosgen 1996)

Channels in a degrading condition may not have true floodplain terraces evident; the former floodplain terraces may take the form of abandoned terraces situated well above the active channel invert such that they no longer receive spills when flows just exceed the actual bankfull discharge. Stream restoration efforts should seek to reestablish a connection to the channel's prior functioning floodplain terraces, or undertake grading measures, if feasible, to create new floodplain terraces adjacent to an appropriately sized bankfull channel. Desirable entrenchment ratios would be similar to those of stable upstream or downstream reference reaches, ideally in the range of about three or greater.

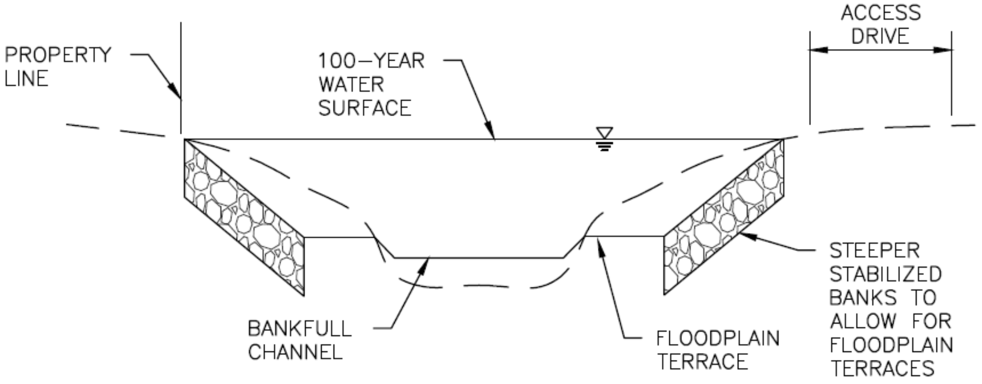
Some stream restoration projects are undertaken in constrained urban channels where natural floodplains have been filled and corridor widths are unnaturally narrow. In these cases, it would still be advantageous to create a bankfull channel with an appropriate width and depth (and width/depth ratio) flanked by adjacent floodplain terraces with a reasonable entrenchment ratio. If a narrow corridor compromises channel shape, it may be better to steepen the outside banks than to reduce or eliminate a stream's floodplain terrace. This is depicted by the proposed improvements illustrated in Figure 8-13; when opening up the existing narrow channel in the limited right-of-way shown in *Existing Section*, it may be preferable to create a shape similar to that in *Proposed Section with Floodplain Terraces* rather than that in *Proposed Section without Floodplain Terrace*.



EXISTING SECTION



DISFAVORED SECTION WITHOUT FLOODPLAIN TERRACES



PREFERRED SECTION WITH FLOODPLAIN TERRACES

Figure 8-13. Creating floodplain terrace in narrow corridor

Sometimes, constrictions in stream corridors lead to locally high velocities. The constrictions may be part of the natural landform or resulting from floodplain filling taking place in the past. Opportunities to pull back banks and open up constricted areas by excavating, reshaping, and revegetating should be pursued. Hydraulics should be checked as described in Section 8.0.

The cross section geometry for all streams should allow for maintenance access. See the *Stream Access and Recreational Channels* chapter for these criteria.

Stream Restoration Principle 3: Establish Effective Cross-Sectional Shape

<u>Representative Design Tasks and Deliverables</u>

1. Document approaches used to size width, depth, shape, and capacity of bankfull channel.
2. Summarize range of proposed entrenchment ratios in project reach and identify steps to be taken to create or maintain floodplain terraces.
3. Confirm that no filling is to take place in floodplain (however, if fill is proposed, document proposed grading limits and hydraulic impacts per Section 4.8).
4. Document minimum freeboard provided to adjacent property elevations.
5. Provide design drawings showing proposed layout of appropriately sized bankfull channel and floodplain terraces in profile and cross section.

4.4 Maintain Natural Planform Geometry

Natural streams offer variety and complexity in form; they are seldom straight and uniform. Outer banks move in and out and bank heights, slopes, and widths vary. Bankfull channels exhibit a degree of meandering and sinuosity, moving right and left across a section in an alternating manner. The shape of the bankfull channel varies as well, tending to widen slightly in bends; side slopes tend to steepen at the outside of bends and flatten as point bars form on the inside of bends. Increasing sinuosity decreases longitudinal slope. Pools can form in the channel bottom at the apex of bends.

Based on typical geometry associated with sand bed streams, meander wavelength (as illustrated in Figure 8-8) may be on the order of 10 to 14 times the bankfull width of the bankfull channel (Leopold 1994). Sinuosity of a channel is defined by the following equation:

$$\text{Sinuosity} = \frac{\text{bankfull channel length}}{\text{valley length}}$$ Equation 8-5

Where the bankfull channel length is measured along the actual channel length and the valley length is measured along the valley.

Refer to Figure 8-8 for graphical representation of the above variables. Sinuosity is often in the range of 1.1 to 1.3 for Front Range streams.

As shown in Figure 8-14, meandering stream forms, especially if there is a presence of gravels or cobbles in the stream bed, may take on a riffle-pool form. In this case, riffles are typically located at the cross-over points between meander bends and pools occur at the outside of the meander bends.

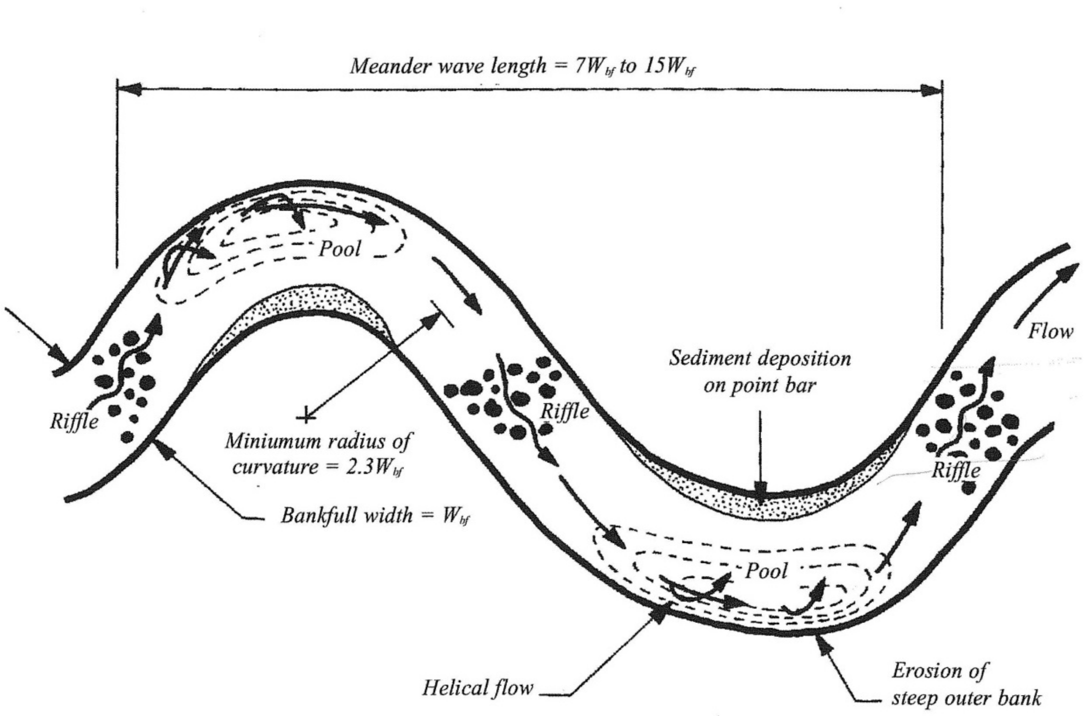


Figure 8-14. Riffle-pool stream form

(Source: Newbury & Gaboury 1993)

If the historic alignment of a natural channel has been altered or disturbed, historic aerial photography may provide useful guides for restoration of the planform geometry. For streams not already altered by past channelization projects and watershed alterations, observations of reference reaches in healthy upstream or downstream reaches or similar stream systems may provide guidance for parameters such as meander amplitude and meander radius.

Figure 8-15 illustrates the planimetric alignment of a reach of Cottonwood Creek upstream of Cherry Creek Reservoir that was reclaimed with a relatively high degree of meandering (with a sinuosity of 1.9) within broad floodplain terraces and an unconstrained right-of-way.

Stream Restoration Principle 4: Maintain Natural Planform Geometry

Representative Design Tasks and Deliverables

1. Document background observations on sinuosity, floodplain width, and meander patterns in study reach or reference reaches and describe basis of proposed stream alignment and planform geometry.
2. Provide design drawings showing plan view of proposed stream restoration improvements.

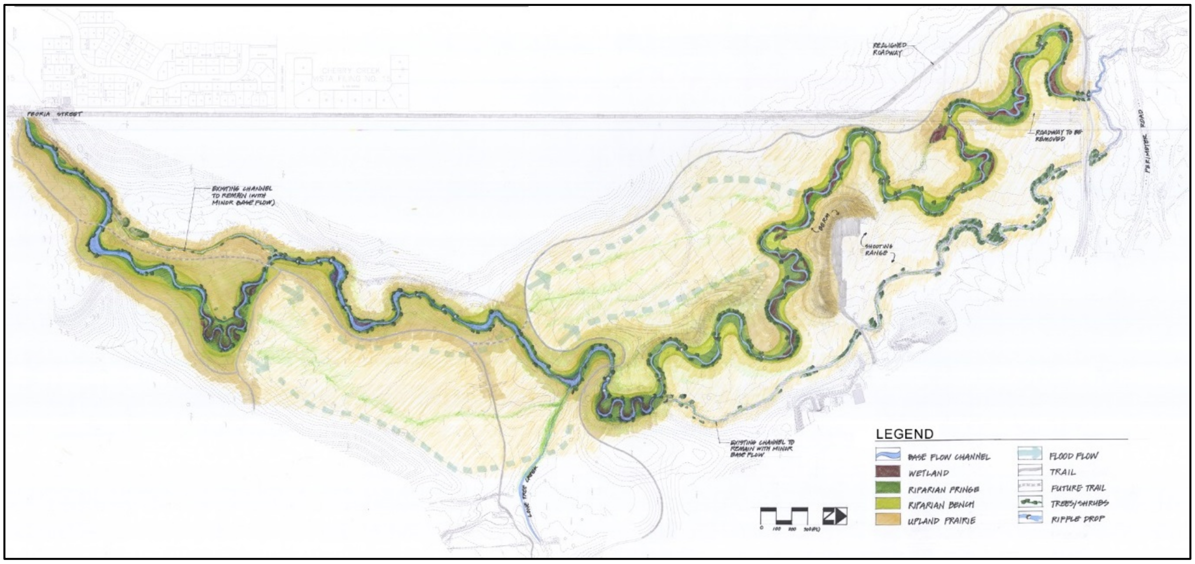


Figure 8-15. Example of meandering single-thread channel form (Courtesy: Wenk and Associates)

4.5 Develop Grade Control Strategy to Manage Longitudinal Slope

As discussed in Section 2.3, a typical stream response to increased urban runoff is to trend toward flatter longitudinal slopes, which, if left unmanaged, leads to degradation and channel incision. A primary management approach to limit degradation is the installation of grade control structures along the length of a stream; the structures hold grade so if the stream wants to flatten its equilibrium slope, incision is limited.

Grade control structures do not create the equilibrium slope of a stream; the stream does. Even a channel filled or constructed at a specific slope will cut or fill within a range of its equilibrium slope. Sometimes a period of high sediment load, which could occur during a large runoff event or result from upstream erosion, will lead to a temporary steepening of the slope, which may reduce during prolonged periods of lower sediment load.

The placement of grade control structures is related to three primary considerations, equilibrium slope, cross sectional capacity, and drop structure height:

Equilibrium slope. Equilibrium slope influences the cumulative drop height needed for a specific stream reach. The estimated equilibrium slope is the flattest slope anticipated in a stream reach over the long term. The actual slope of a stream may vary over time. It is possible that an open channel may exhibit a steeper slope than the estimated equilibrium slope for periods of time, especially if a stream is subject to a high sediment load. At other times slopes may flatten in response to lower sediment loads. Plan to construct check structures with the assumption that these buried structures will eventually become drop structures and, based on the minimum estimated equilibrium slope, will not be undermined. If the channel maintains a steeper slope, or temporarily steepens in response to high sediment loading conditions, this may lead to a partial burying of grade control structures, but without negative effect. The term “grade control structure” generally refers to structures intended to reduce the channel slope and control the elevation of the channel invert (i.e., check structures and drop structures). See the *Hydraulic Structures* chapter for more information.

If the long-term equilibrium slope of the bankfull channel is less than the longitudinal slope of the adjacent terraces, grade control structures are required with the intent of achieving the appropriate slope between the structures. The location of grade control structures can be determined by extending the estimated equilibrium slope from the crest elevation of a downstream grade control structure to the downstream invert of the next grade control structure upstream. Several approaches are available to estimate long-term equilibrium slope:

1. In streams not already altered by past channelization projects, equilibrium slope can be estimated using a reference reach approach. This is a qualitative fluvial geomorphology method that correlates equilibrium slopes from similar streams that have undergone changes (aggradation or degradation) in slope in response to urban development. Reference reaches have similar geomorphic characteristics as the project reach such as watershed size, watershed imperviousness, soil type, bed material, sediment loading, etc. In addition, the reference reach must be in equilibrium conditions and not unduly influenced by unstable upstream conditions (i.e., high sediment loads from eroding upstream channels or tributaries). Reference reach evaluations require familiarity and experience in geomorphology and river mechanics.

2. Sediment equilibrium analyses can be undertaken to estimate a longitudinal gradient that will provide for a balance between the expected inflow of water and sediment to a reach and the ability of the reach to convey that water and sediment without significant long-term aggradation or degradation. Like the reference reach approach, sediment equilibrium analyses require familiarity and experience in geomorphology and river mechanics.

3. Equilibrium slope may have been estimated in an UDFCD master plan.

4. A conservative low estimate of equilibrium slope for many urban stream systems within UDFCD boundaries is between zero and 0.2 percent. Sandy channel reaches subject to perennial flows in watersheds with significant urbanization and very low sediment load have been observed in the field at a near zero percent slope. Grade control structures laid out based on a zero or near-zero percent slope may at times of higher flow, higher sediment loading, and slightly steeper slope have their vertical drop height reduced on a temporary basis, but generally without negative effect as long as the sediment load and level of aggradation is not excessive.

Once a minimum equilibrium slope has been estimated, the overall drop structure height for a reach is the product of the reach length and the difference between the equilibrium slope and the actual slope or the floodplain terrace slope.

<u>Cross sectional capacity</u>. Drop structures are designed to span across the bankfull channel and some portion of the floodplain and are intended to tie into both floodplain terraces of the channel. In some streams, the grade control structures are designed to extend across the full width of the channel from outside bank to outside bank; these drop structures fully convey the capacity of the channel, which could include the 100-year event. This is depicted in Figure 8-16.

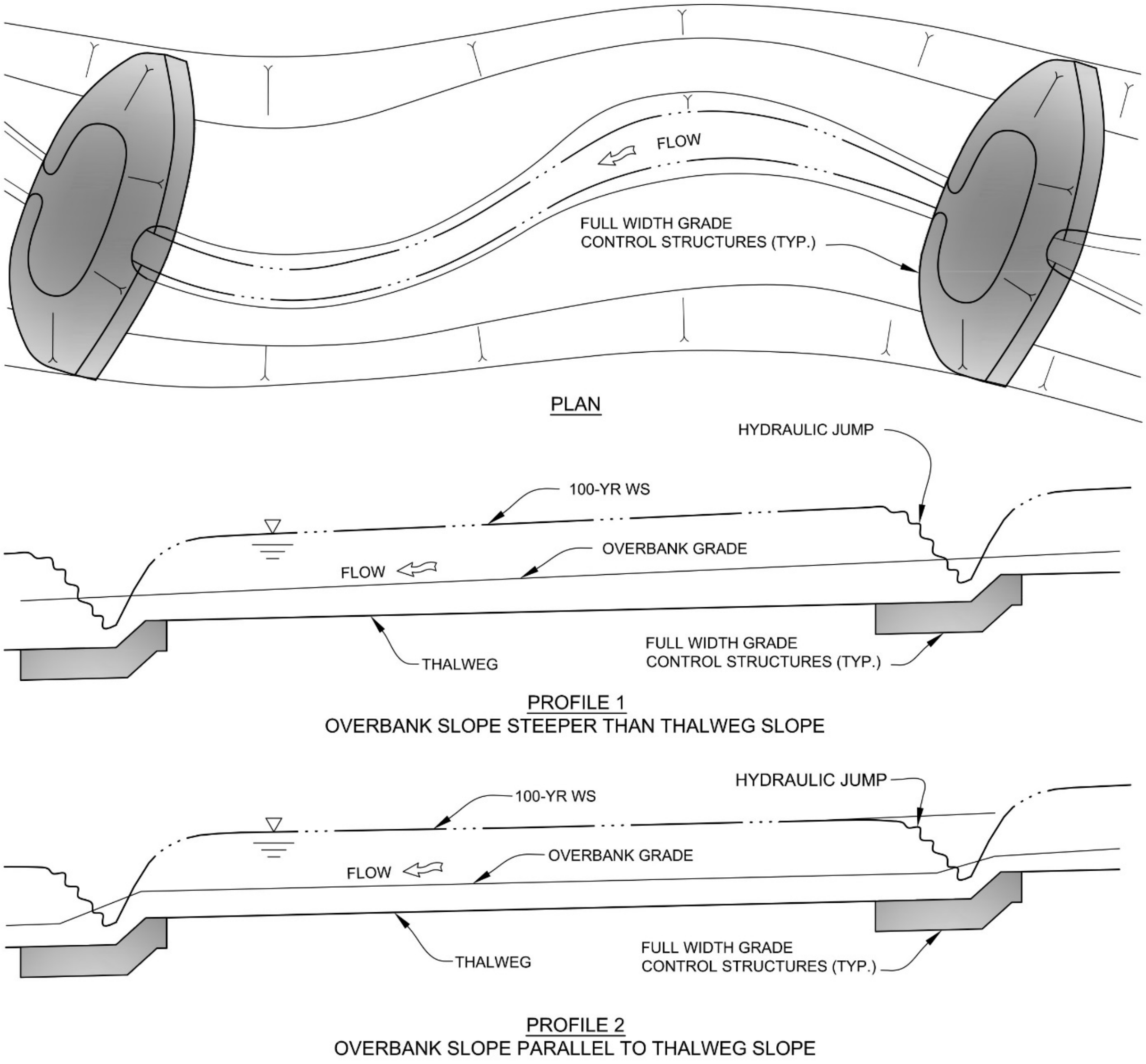


Figure 8-16. Full width grade control structures

Two longitudinal profiles are shown in Figure 8-16. The first assumes that the bankfull channel invert develops a long-term equilibrium slope that is flatter than the adjacent floodplain terraces; in this case the depth of the bankfull channel varies and is typically at a minimum just upstream of a grade control structure and a maximum just below the next drop structure upstream.

The second profile shows the slope of the floodplain terraces parallel to the invert of the bankfull channel. This case could occur when there is a natural drop in grade across the whole width of the channel, or when a design includes re-grading the terraces and a constant bankfull channel depth is maintained. In each profile, hydraulic jumps are shown to occur at the full-width grade control structures.

In other streams, especially in the larger ones, grade control structures may be designed to tie into the intermediate channel banks of the floodplain terraces that may have a capacity less than the 100 year peak flow. This concept is depicted in Figure 8-17. The grade control structures may have a capacity of a 20-year, 2-year, or just a bankfull channel event.

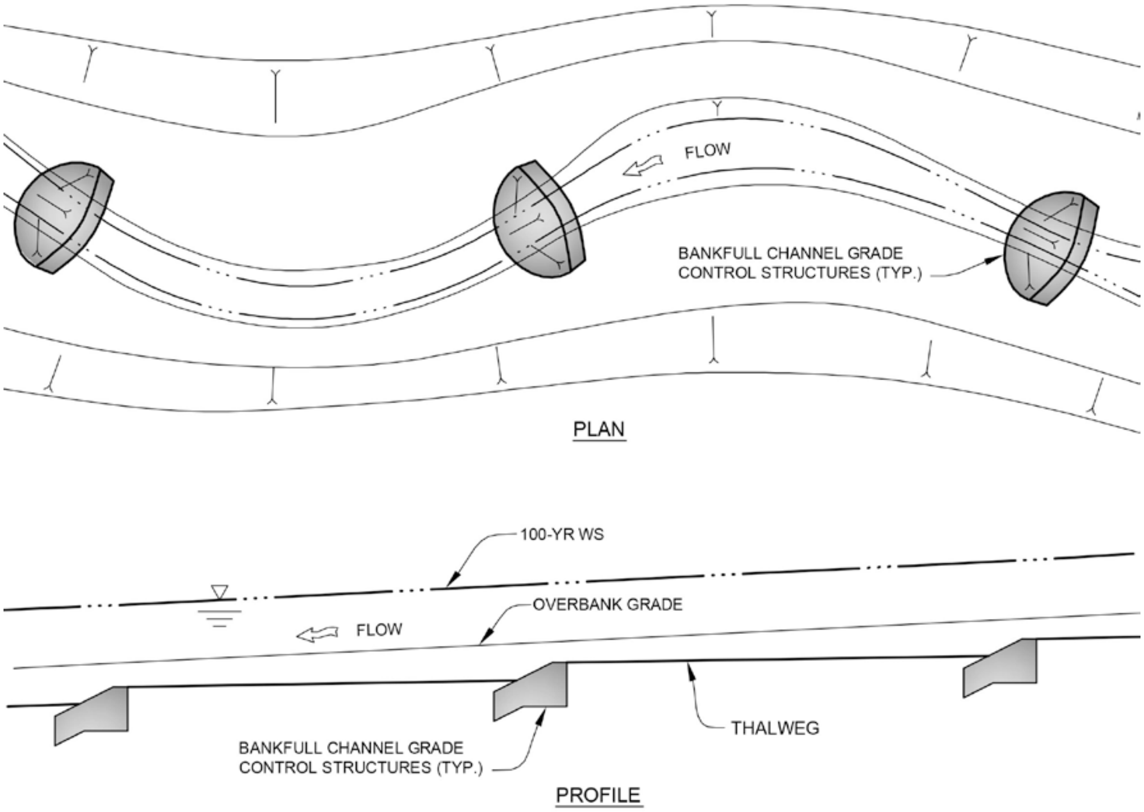


Figure 8-17. Bankfull channel grade control structures

Drop structures with capacities less than the 100-year event must be thoroughly analyzed to verify acceptable performance and stability during the 100-year event within the drop structure itself and in the adjacent terrace areas that will experience flow during the 100-year event. Often, the cutoff wall or sheet piling for a drop structure with a capacity less than the 100-year event will be extended substantially beyond the limits of the drop structure, sometimes to the limits of the 100-year floodplain.

Like the first profile of Figure 8-16, the longitudinal profile for bankfull drop structures reflects a bankfull channel longitudinal slope that is flatter than the longitudinal slope of the adjacent floodplain terraces. The depth of the bankfull channel varies and is typically at a minimum just upstream of a grade control structure and a maximum just below a drop structure; however, since drop structure spacing is typically more frequent for bankfull channel drop structures than full-width drop structures, the variation in channel depth is typically less. Bankfull channel drop structures are generally designed to drown out during large, infrequent floods such as the 100-year event and thus hydraulic jumps are not shown.

Drop structure height. In general, more frequently spaced low-height drop structures work best for flows smaller than the 100-year event. The most appropriate height should be verified through hydraulic analyses but may be less than a foot in height up to two feet. These small drop structures create less energy to dissipate, are better for fish passage integration, and can frequently be shown to drown out at higher flows, as shown in the profile of Figure 8-17. Figure 8-14 provides an example of how low-height drop structures can be incorporated into stream restoration design; it shows how drop structures in natural sand or cobble streams can consist of rock riffles located at crossovers between meander bends.

Stream Restoration Principle 5: Develop Grade Control Strategy to Manage Longitudinal Slope

Representative Design Tasks and Deliverables

1. Document estimate of long-term equilibrium slope used for drop structure spacing and its basis.
2. Describe rationale for selection of bankfull channel grade control structures or full-width structures, design capacity, heights of drops, and types of drops.
3. Confirm if fish passage is applicable and provided.
4. Document hydraulic design of grade control structures (refer to Sections 4.8, 7.0, and Hydraulic Structures chapter).
5. Provide design drawings showing grade control structures in plan, profile, section, and details.

4.6 Address Bank Stability

Existing steep, unstable banks at the edges of the bankfull channel or at outer channel banks should be addressed. Consider the following methods in the order that they are presented:

- Vegetation measures.
- Bioengineering measures that strategically combine vegetation with various means of reinforcements such as coir blankets, willows in various configurations, turf reinforcement mats (TRMs), or soil- or void-filled riprap.
- Structural measures such as riprap and boulders.

4.6.1 Bioengineering Techniques

Over the course of decades, the practice of stream restoration within UDFCD has evolved from the use of structural measures to an approach that first considers vegetation, then bioengineering techniques prior to hard structural measures. UDFCD promotes the integration of bioengineering techniques into stream restoration design when the use of these measures is consistent with the policies concerning flow carrying capacity, stability, and maintenance.

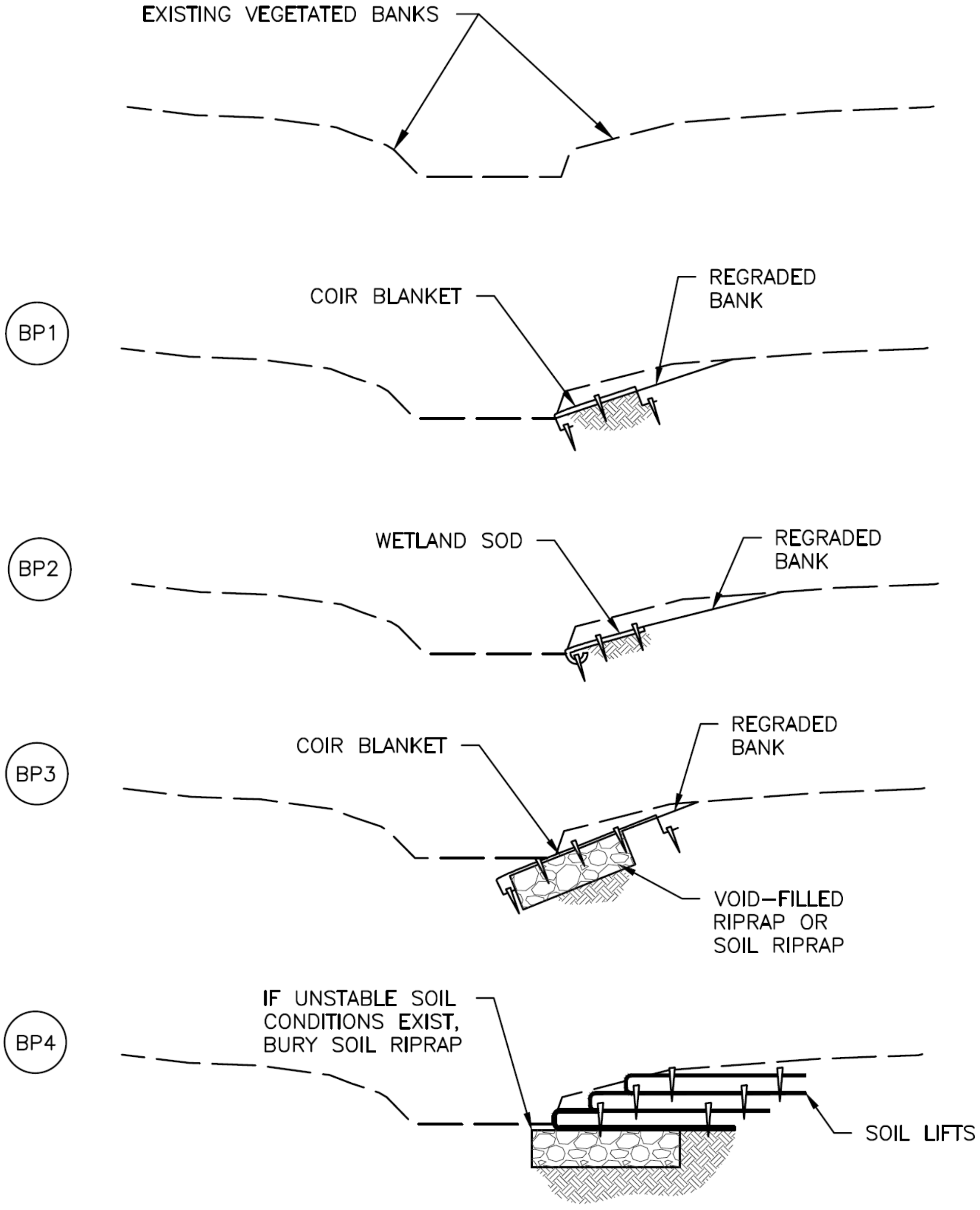
Compared to structural measures alone, vegetation and bioengineering appear more natural in character, enhance habitat, increase roughness to reduce velocities, may be of lower cost, and can create a living system that becomes stronger with time. On the other hand, care is necessary to select methods and vegetation suited to the hydrology of the stream, increased roughness of mature vegetation reduces flood conveyance capacity, and during the early years of establishment the risk of damage from large flood events may be greater than if more extensive structural measures are used. Many bioengineered stream restoration efforts have failed because the designer underestimated the stream power during large runoff events, or the likelihood of such events occurring during the vulnerable first several years of the newly established vegetation.

The advantages and risks of bioengineering techniques need to be taken into account by designers when selecting bank protection measures. As mentioned in Section 4.1, observing and understanding existing bank conditions, flow characteristics, causes of existing erosion, the potential for future erosion, and the proximity of infrastructure or property that could be impacted are necessary to design appropriate bank protection.

4.6.2 Bank Protection Approaches

Figure 8-18 shows several example approaches for protecting unstable banks along the bankfull channel. Photographs 8-11 through 8-16 illustrate a number of bioengineering approaches.

Because bank erosion may be more pronounced on the outside of bends, treatments may differ between the outside and inside. Treatments shown in Figure 8-18 generally apply to the outside bank. However, depending on stream conditions, any of these bank treatments may be implemented on the inside bank as well.



NOTES:
1. BANK PROTECTION TREATMENTS ARE SHOWN APPLIED TO RIGHT BANKS, BUT ARE APPLICABLE TO TO EITHER BANK.
2. TREATMENT SHOWN ARE FOR SCHEMATIC PURPOSES ONLY. THE DESIGNER IS RESPONSIBLE FOR FINAL DESIGN OF ALL TREATMENT INCLUDING STAKING PATTERNS, ROCK SIZING, ETC.

Figure 8-18. Example low-flow channel bank protection treatments

Photograph 8-11. Bioengineering techniques for channel stabilization immediately following construction.

Photograph 8-12. Same view as photo 8-11, one year after construction.

Photograph 8-13. Coir blanket used to protect the outside banks of a low-flow channel immediately following construction.

Photograph 8-14. (Same view as photo 8-13) Dense established vegetation.

Photograph 8-15. Soil lifts used to stabilize banks of low-flow channel. Photo taken immediately after construction.

Photograph 8-16. (Same view as photo 8-15 taken one year following construction.)

Photograph 8-17. Void-filled riprap used to stabilize the low-flow channel.

Severe bank erosion can occur when a low-flow channel migrates into a high outer bank, undermining the toe of the bank and causing a steep eroded face. Figures 8-19A and 8-19B show a number of examples for stabilizing and protecting this type of bank erosion. Like Figure 8-18, the bank protection approaches shown on the right side typically represent the outside bank.

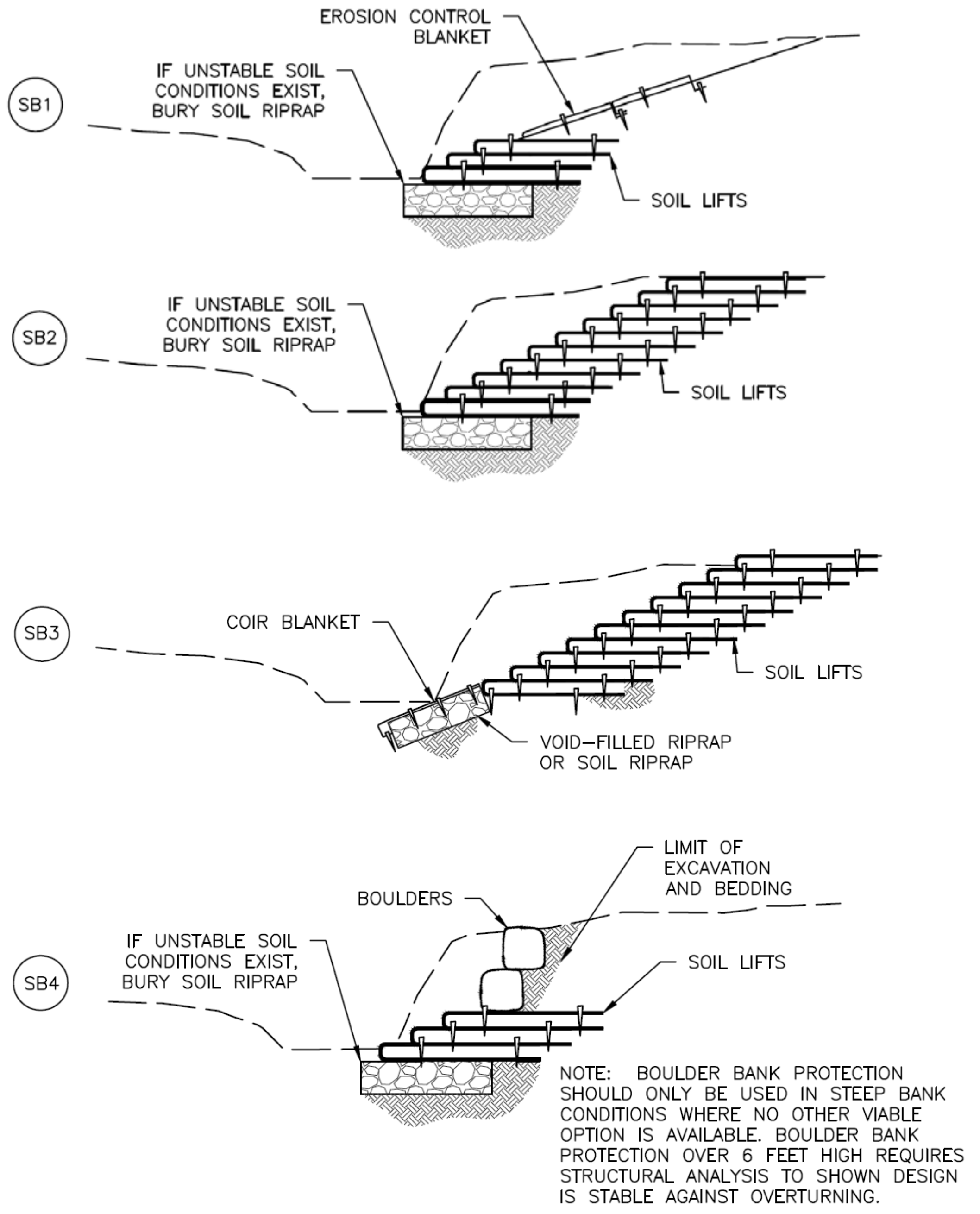
Designers must weigh the imposed shear stresses during floods of various magnitudes and locations to the resistive shear of the vegetation and soil. Methodology for assessing shear resistance of vegetation is discussed in Section 4.7. UDFCD recommends using purely vegetative treatments when the vegetation can provide adequate protection for the bank. In areas where immediate protection is required, this approach may include the use of wetland sod. Biooengineered solutions such as soil lifts (see Figure 8-20), can be used to offer a higher level of protection in the initial years after construction, allow steeper construction, and also help establish vegetation. The material used for typical soil lift construction consists of a combination of coconut fabric and coir. In some locations more “permanent” turf reinforcement mats can be used within a soil lift to withstand shear stress in excess of vegetation alone.

The use of soil-filled and void-filled riprap for bank protection should undergo hydraulic design using the methods described in Section 8.0. Rock and boulders can be used when vegetative and bioengineered practices won’t provide adequate bank protection. UDFCD experience has shown that bank treatments relying on boulders tend to be more susceptible to scour and undermining; therefore, the use of boulders should be limited to entrenched channel conditions and tight radii where vegetative methods are viewed as less viable. Grouted boulders require adequate foundation and proper backfill. See Figure 8-36 for a detail. As shown in Figure 8-19A and 8-19B, boulder bank protection over six feet high requires structural analysis to demonstrate that the design is stable against overturning.

Stream Restoration Principle 6: Address Bank Stability

<u>Representative Design Tasks and Deliverables</u>

1. Describe rationale for selection of bank protection measures, considering vegetative, bioengineering, or structural approaches. Determine whether the stream’s hydraulic response to extreme events makes it suitable for bioengineering and vegetative approaches. This includes consideration of shear stress during floods of various magnitudes.
2. Provide design drawings showing bank protection layouts in plan and section.
3. Provide supporting hydraulic calculations for selected bank protection.



NOTE: BOULDER BANK PROTECTION SHOULD ONLY BE USED IN STEEP BANK CONDITIONS WHERE NO OTHER VIABLE OPTION IS AVAILABLE. BOULDER BANK PROTECTION OVER 6 FEET HIGH REQUIRES STRUCTURAL ANALYSIS TO SHOWN DESIGN IS STABLE AGAINST OVERTURNING.

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Figure 8-19A. Example bank protection treatments for steep eroded banks

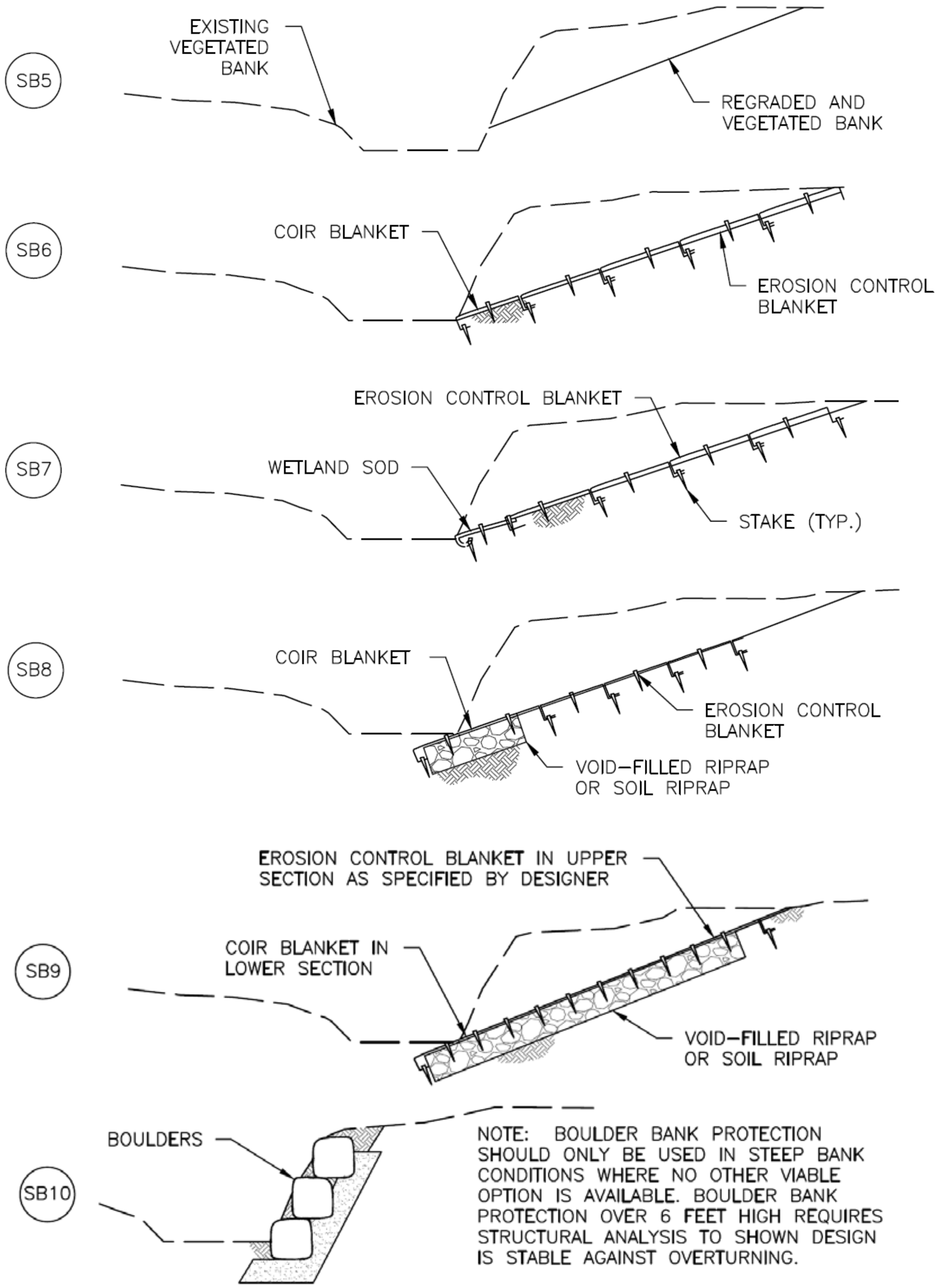

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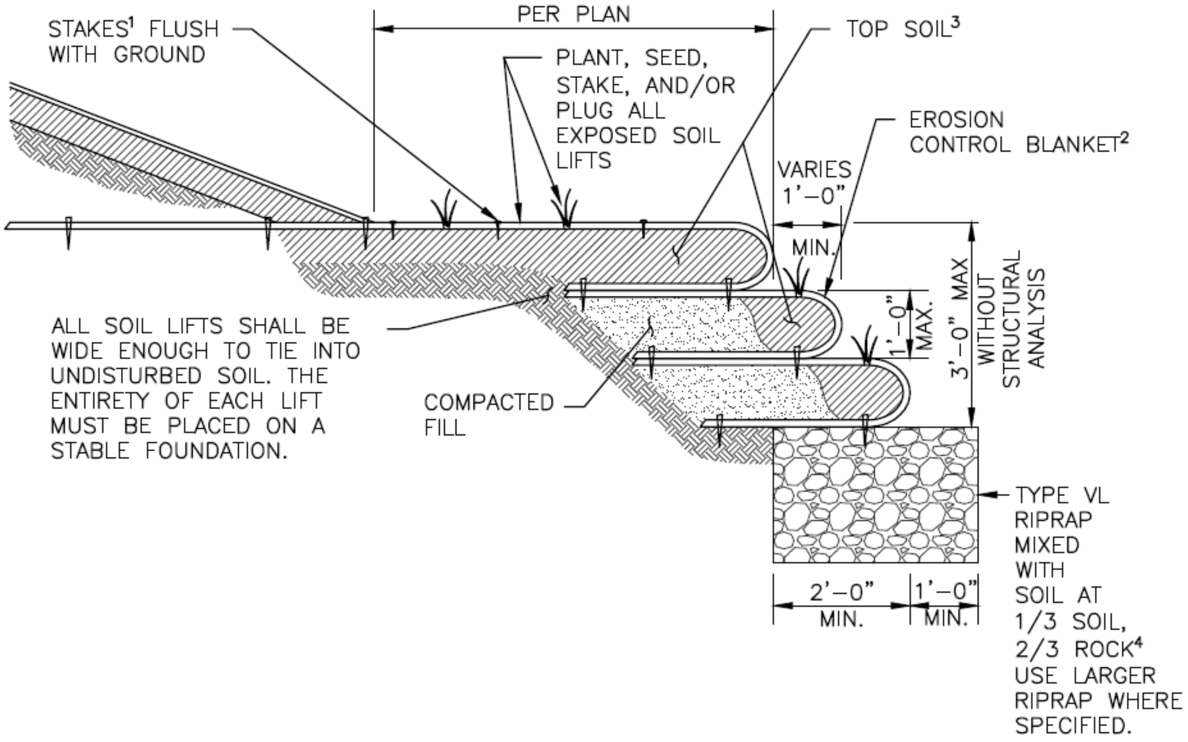
Figure 8-19B. Example bank protection treatments for steep eroded banks



1. SEE FIGURE 13-5 IN REVEGETATION CHAPTER.
2. SPECIFY MATERIALS BASED ON HYDRAULIC CONDITIONS. MINIMIZE SEAMS, SPECIFYING MATERIAL WITH A WIDTH WIDE ENOUGH TO PLACE FABRIC PARALLEL TO FLOW. ALL FABRIC SHOULD BE PLACED TIGHT TO SOIL.
3. SEE REVEGETATION CHAPTER.
4. RIPRAP MAY NOT BE REQUIRED IN ALL LOCATIONS. THIS MAY BE ELIMINATED WHERE HYDRAULIC CONDITIONS DO NOT WARRANT RIPRAP AND THE ENGINEER DETERMINES SUBGRADE TO BE STABLE.

Figure 8-20. Sample soil lift section

4.7 Enhance Streambank and Floodplain Vegetation

As described in Section 4.6 in relation to bioengineering approaches, it is desirable to re-establish or supplement vegetation in stream corridors, especially along the banks of the low-flow channel and on the adjacent floodplain terraces to build up a sturdy, durable cover to help retard flood flows, resist erosion, and enhance habitat. Establishing a relatively shallow bankfull channel as described in Section 4.3 can help maintain a shallow water table favorable for terrace vegetation.

Deep-rooted riparian grasses such as Prairie Cordgrass, sedges, rushes, and other herbaceous species can provide excellent shear resistance to protect streambanks and floodplain terraces. Willows possess an amazing ability to root and thrive in streamside environments and are an important element in bioengineered bank protection; however, it is desirable to create a diverse mix of herbaceous species, woody shrubs, and trees within the floodplain and to avoid establishing a dominant monoculture of willows. Willows can also create a very dense stand of vegetation that may ultimately impact flood conveyance.

Analysis of the stability of grass lined channels should be completed using the stability procedures documented in the Agricultural Research Service (ARS) *Agricultural Handbook Number 667* (hereinafter referred to as *Handbook #667*). Developed in 1987, Handbook *#667* includes comprehensive methods for evaluating shear stress on grass and the underlying soil based upon grass height, density and soil type.

U.S. Army Corp. of Engineers, through its Ecosystem Management and Restoration Research Program (EMRRP), also provides a good resource for evaluating shear stress for a number of different channel lining methods in *Stability Thresholds for Stream Restoration Materials* (Fischenich 2001). Another resource for shear stresses of various vegetation and bioengineering methods is Table TS14I–4 in Technical Supplement 14I, *Streambank Soil Bioengineering* (USDA 2007).

The soil compaction effects of heavy equipment engaged in stream restoration work must be mitigated to help revegetation efforts. Compacted ground must be thoroughly deep-tilled and topsoil previously stripped and stockpiled needs to be replaced and fine-graded in disturbed areas prior to seeding and planting. If inadequate existing topsoil is available, topsoil meeting specified agronomic characteristics should be imported.

Bioengineering Tips

1. When using blankets or mats parallel to the channel, avoid grade breaks in the middle of the blanket or mat run. Consider using soil wraps at these locations to provide better channel definition.
2. Ensure blankets and mats meet manufacturers' shear stress and velocity limits under critical flows in an unvegetated state. Use a safety factor as these tests are not typically performed for extended durations. (Fischenich 2001)
3. In areas subject to flow, blankets must be installed to hold the seed and soil in place. Placing seed and then straw and staking coir fabric over the straw is commonly used to achieve this. See the *Revegetation* chapter for a detail.
4. Consider using larger wooden stakes at toes and in trenches while using biodegradable stakes through the middle and upper sections of blankets and mats. This reduces obstacles for maintenance operations and recreational users.
5. Consider the area where the bank meets the channel bottom carefully. Reinforcement with wetland sod, willow logs, etc. can help ensure success.

Because of the challenges involved in getting vegetation established in areas disturbed by construction as well as the importance of early establishment to the function of a stream, follow-up activities must be planned over a several-year period to nurture vegetation efforts. Activities such as weed control, supplemental watering, reseeding, and replanting need to be planned, budgeted, and executed diligently to help disturbed areas fully recover and be protected with a healthy, varied mix of riparian vegetation. Streams that are constrained in terms of flood capacity require periodic maintenance activities to thin floodplain vegetation and reduce roughness.

Chapter 12, *Revegetation*, provides detailed guidance regarding revegetation efforts in stream corridors.

Stream Restoration Principle 7: Enhance Streambank and Floodplain Vegetation

Representative Design Tasks and Deliverables

1. Identify areas of existing riparian vegetation that will be preserved and fenced off during construction.
2. Document approach and rationale for revegetation, identifying general seed mixes and types of plantings. Confirm that hydrology is suitable for vegetation selected.
3. Provide design drawings showing a detailed vegetation plan, including seed mix and planting details and specifications for loosening compacting disturbed soils and establishing adequate topsoil.

4.8 Evaluate Stream Hydraulics of over a Range of Flows

Detailed hydraulic modeling of stream corridors with proposed restoration improvements is required to assess flow depths, velocities, Froude number, imposed shear stress and other relevant parameters. The hydraulic analysis should consider a range of flows including the bankfull discharge, 2-year, 10-year, 100-year, and perhaps other intermediate and larger flows.

Section 7.0 provides guidance for conducting hydraulic modeling. The hydraulic modeling provides important information to guide the design of stream restoration improvements. It is recommended that hydraulics be evaluated for three conditions:

1. Baseline conditions reflecting estimated historic, unconstrained channel configuration, vegetation, and pre-development flow rates, if such conditions can be estimated.
2. Existing channel conditions based on estimated future development flow rates.
3. Proposed conditions representing the designed stream restoration improvements.

In each case, hydraulic parameters should be summarized for average flow conditions in the channel as well as independently in the main channel and terraces. The following hydraulic summaries are recommended:

- Longitudinal profiles showing bed invert, any grade control structures, and water surface profiles for a range of return periods.
- Longitudinal summaries of flow velocities and shear stress for the main channel and left and right terraces referenced to the same stationing as the profile information above.
- Cross section distributions of velocity and shear stress at representative locations along a design reach.

Section 7 provides guidance and examples of this hydraulic information. The overall goal is to use the information to assess in what ways and to what extent existing channel and hydraulic conditions depart from baseline conditions and to identify proposed stream improvements that create or restore healthy stream form, hydraulic conditions, and sediment equilibrium.

It is important to test the sensitivity of varied channel roughness – low roughness estimates for velocity and shear considerations and high roughness estimates for water surface determinations. Additional guidance on roughness estimates is provided in Section 7.0. Based on anticipated species and densities of vegetation and the in situ soil characteristics, it is necessary to confirm that imposed shear stress is less than shear resistance of soil/vegetation for the intended design event. Section 4.7 describes resources available to support these evaluations. In addition, rock sizing procedures are described in Section 8.0. The hydraulic analysis effort is normally iterative, requiring refinements to the design to obtain desired hydraulic conditions.

Table 8-1 summarizes desirable geometric and hydraulic design parameters for naturalized channels. This table should be used as a guide for determining the stability of a channel. The designer’s experience and judgment are also an important aspect of determining channel stability. Although recommendations for maximum tractive force (or shear stress) are provided, the designer may elect to assess the resistive shear stress provided by terrace vegetation and soils and determine design limits specific to the project.

Since the subject of this Section 4 is restoring natural streams, it may be that the maximum prudent values for the hydraulic parameters shown in Table 8-1 are exceeded in the 100-year event even after the recommendations of subsections 4.1 through 4.8 are followed, including avoiding filling the floodplain, establishing a shallow bankfull channel with adjacent vegetated terraces, opening up constrictions, implementing grade control structures, and enhancing vegetation. The goal would be to come as close as possible for as much of the reach as possible to the maximum prudent values for the hydraulic parameters in the 100 year event. The designer should determine the return period where these parameters would be achieved and, with the owner and local jurisdiction, determine if the associated risks are acceptable.

On the other hand, if the recommendation to avoid floodplain filling is not followed and fill is proposed, this should only happen in floodplains where the maximum prudent values for the hydraulic parameters shown in Table 8-1 are not exceeded in the 100-year event.

Table 8-1. Maximum prudent values for natural channel hydraulic parameters

Design Parameter	**Non-Cohesive Soils or Poor Vegetation**	**Cohesive Soils and Vegetation**
Maximum flow velocity (average of section)	5 ft/s	7 ft/s
Maximum Froude number	0.6	0.8
Maximum tractive force (average of section)	0.60 lb/sf	1.0 lb/sf
Maximum depth outside bankfull channel	5 ft	5 ft

Stream Restoration Principle 8: Evaluate Hydraulics of Streams over a Range of Flows

<u>Representative Design Tasks and Deliverables</u>

1. Document hydraulic analyses of the project reach following the guidance of Section 7.0.
2. Describe how hydraulic performance of the project reach compares to maximum prudent values for the hydraulic parameters shown in Table 8-1 for several return periods (including 2-, 10-, and 100-year events at a minimum). Describe any locations in the reach where these parameters are exceeded and discuss efforts made to improve hydraulics.
3. Confirm that hydraulic parameters of Table 8-1 are satisfied in for the100-year event in all locations where fill is proposed in the floodplain.

5.0 Naturalized Channels

Natural channels may not be well-defined in upland tributary areas and it may be necessary to construct new channels "from scratch." By applying principles from Section 4, new surface channels can be created that emulate natural streams and, over time, may take on the appearance and functions of natural streams with supporting vegetation and biota. The criteria and techniques presented in this section may also be used on some existing stream reaches where existing urban constraints are limiting.

Naturalized channels do not have concrete trickle channels and are generally not intended to be vegetated with irrigated sod; rather, native grasses and riparian species are recommended. Vegetation at the edges of the low-flow channel and in the adjacent floodplain terraces is generally not intended to be mowed to a low height. Current criteria in this manual do not address bare rock riprap-lined channels or concrete-lined channels, since these are not recommended as typical channel treatments. Design guidelines for these types of channels can be found in other manuals.

Remember Permitting Requirements

The environmental permitting process benefits greatly from early and close coordination with the US Army Corps of Engineers. Environmental firms experienced in 404 permitting not only make the process efficient and successful but provide valuable expertise on restoration projects. The stream restoration principles described in this chapter represent good practice and are consistent with the intent of the 404 permit system to protect waters of the US. In addition, Endangered Species Act (ESA) requirements must be addressed for Conditional Letters of Map Revisions

These projects also frequently require Federal Emergency Management Agency (FEMA) map changes. See the *Flood Risk Management* chapter for guidance.

The eight stream restoration principles from Section 4 apply directly to the design and construction of naturalized channels. These are summarized below; the designer is encouraged to review the applicable information in the corresponding Sections 4.1 through 4.8.

5.1 Understand Existing Stream and Watershed Conditions

For naturalized channels, the goal of this principle is to locate candidate reference reaches that have desirable geometric, hydraulic, and vegetative characteristics that can be used as a guide for the design of the project reach. Ideally, reference reaches would serve about the same upstream area and convey similar flow rates; however, desirable reference reaches serving larger or smaller areas may be able to be scaled to match the design flows of the naturalized channel. In many cases however, no applicable reference reach will exist, in which case the bankfull channel sizing methods described in Section 4.3.2 should be applied.

Researching design flows and understanding characteristics of the watershed upstream of the naturalized channel involves the same types of information and yields the same benefits as described for natural streams in Section 4.1. As a first step, every effort should be made to apply runoff reduction methods in upstream watershed areas. The more runoff reduction upstream, the lower the range of flow rates, velocities, and shear stresses, the less structural the stream improvements need to be and the higher the water quality of runoff. The relative increase in flows from pre-development conditions to future build-out are to be evaluated as part of understanding the existing stream and watershed conditions for the naturalized channel.

5.2 Apply Fluvial Geomorphology Principles to Manage Sediment Balance

While sediment loading may not be a design consideration for naturalized channels draining small watersheds, it is still advisable to consider sediment movement and fluvial channel characteristics. A relatively small upstream drainage area combined with a low sediment load may translate into a channel that can support vegetation across the bottom of the bankfull channel. This type of channel may resist bed degradation better than an unvegetated channel bottom and therefore be able to maintain a slightly steeper longitudinal slope, driven less by a need to control baseflow erosion and more by the desired overall channel hydraulics in the design storm.

5.3 Establish Effective Cross-Sectional Shape

Creating a properly sized bankfull channel with adjacent vegetated floodplain terraces is a critical element in the design of naturalized channels. Sizing of the bankfull channel as described in Section 4.3.2 can be applied to these channels; however, Table 8-2 provides minimum dimensions for bankfull channels and floodplain terraces in naturalized channels. Figure 8-21 defines the geometry addressed in Table 8-2 for a naturalized channel.

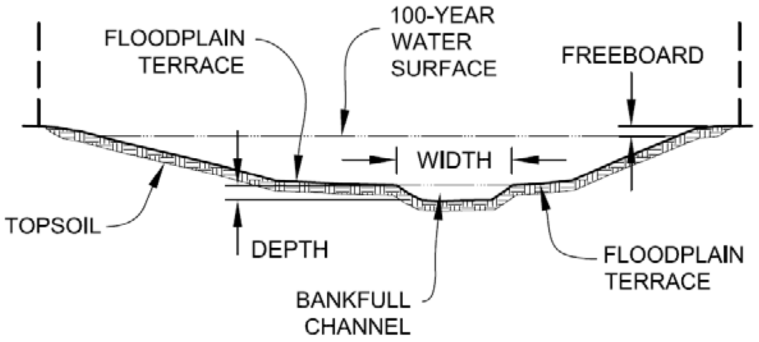


Figure 8-21. Typical naturalized channel geometry

The bankfull channel in naturalized channels should be sized to convey at least 70% of the future development 2-year flow or 10% of the future development 100-year flow, whichever is greater. In addition to the minimum dimensions shown in Table 8-2, a maintenance access path with a minimum per the geometry listed in Table 9-3 of the *Stream Access and Recreational Channels* chapter.

Table 8-2. Minimum dimensions for naturalized channels[1]

Bankfull Channel Depth, ft	Minimum Bankfull Channel Width, ft	Minimum Floodplain Terrace Width (average each side), ft
0.5	6	6
1.0	10	8
1.5	14	10
2.0	18	12
2.5	24	16
3.0	30	20

[1] Values are based on a desired entrenchment ratio between 3 and 4. Based on several scenarios modeled in HEC-RAS, the values in this table, when paired with the criteria in Table 8-3, produce generally favorable hydraulics.

As in natural streams, channel vegetation and roughness will increase over time and long-term sediment deposition could raise the bed of the channel. Therefore, conservatively high roughness values should be used for assessing flow depths (per Section 7.0) and a freeboard of 18 inches or more should be considered.

5.4 Maintain Natural Planform Geometry

The planform of naturalized channels can be created to emulate features of natural reference reaches. As was discussed in Section 4.4, natural streams offer variety and complexity in form; they are seldom straight and uniform. Outer banks move in and out and bank heights, slopes, and widths vary. Bankfull channels exhibit a degree of meandering and sinuosity, moving right and left across a section in an alternating manner. The shape of the low-flow channel varies, tending to widen slightly in bends and narrow in riffles between bends; side slopes tend to steepen at the outside of bends and flatten as point bars form on the inside of bends. All of these characteristics can be reflected in naturalized channels.

Care should be taken to avoid sharp bends in the channel. A radius of curvature at least two times the channel top width is recommended, although ratios of three or four times top width are preferable.

5.5 Develop Grade Control Strategy to Manage Longitudinal Slope

If the grading adjacent to a channel can be made to match the design slope of the channel, the need for drop structures may be eliminated. If the adjacent grade is steeper than the design slope, grade control in the channel will be necessary. For small channels, grade control structures will most often extend across the full channel section and the grade of the floodplain terraces will typically be configured to match the design slope of the bankfull channel invert. Section 4.4 should be referred to for design guidance regarding the height and spacing of drop structures.

5.6 Address Bank Stability

Constructed naturalized channels will not typically have extensive bank erosion problems to address; however, bank protection for low-flow channel banks or outer banks may be incorporated into the design, particularly on the outside of bends. Bank protection measures can be determined based on the options identified in Section 4.6. Bioengineering applications for bank protection may be considered for naturalized channels given acceptable hydraulic response (e.g., stream power) to extreme events.

5.7 Enhance Streambank and Floodplain Vegetation

The naturalized channel should be seeded and planted with herbaceous and woody species appropriate for anticipated hydrologic conditions in zones adjacent to the bankfull channel as described in Section 4.7 and the *Revegetation* chapter of this manual. It is critical that the soil compaction effects of heavy equipment be mitigated to help revegetation efforts. Compacted ground must be thoroughly deep-tilled, amended and topsoil previously stripped and stockpiled needs to be replaced and fine-graded in the channel prior to seeding and planting.

Topsoil

Topsoil is a valuable resource. Where present, remember to strip, stockpile and use this material. Because of the importance of favorable soil characteristics for plant health, naturalized channel projects may call for 12 inches of topsoil for the full width of the channel. See the Revegetation chapter for additional recommendations.

In addition, a post-construction maintenance phase should be planned for watering, weed control, and supplemental seeding/planting to ensure vegetation establishment.

5.8 Evaluate Stream Hydraulics over a Range of Flows

Conduct detailed hydraulic modeling of naturalized channels, applying low roughness estimates for velocity and shear considerations and high roughness estimates for water surface determinations, as described in Section 7.0. Confirm that imposed shear stress is less than the shear resistance of soil/vegetation for the intended design event and refine the design to obtain the hydraulic conditions identified in Table 8-3, below. Note that the parameters listed in this table assume cohesive soils and vegetation; however, it is recommended that these values be satisfied for roughness conditions that will exist immediately after construction.

Table 8-3. Design parameters for naturalized channels

Design Parameter	Design Value
Maximum 100-year depth outside of bankfull channel	5 ft
Roughness values	Per Table 8-5
Maximum 5-year velocity, main channel (within bankfull channel width) (ft/s)	5 ft/s
Maximum 100-year velocity, main channel (within bankfull channel width) (ft/s)	7 ft/s
Froude No., 5-year, main channel (within bankfull channel width)	0.7
Froude No., 100-year, main channel (within bankfull channel width)	0.8
Maximum shear stress, 100-year, main channel (within bankfull channel width)	1.2 lb/sf
Minimum bankfull capacity of bankfull channel (based on future development conditions)	70% of 2-year discharge or 10% of 100-yr discharge, whichever is greater[1]
Minimum bankfull channel geometry	Per Table 8-2
Minimum bankfull channel width/depth ratio (Equation 8-3)	9
Minimum entrenchment ratio (Equation 8-4)	3
Maximum longitudinal slope of low flow channel (assuming unlined, unvegetated low flow channel)	0.2 percent
Bankfull channel sinuosity (Equation 8-5)	1.1 to 1.3
Maximum overbank side slope	4(H):1(V)
Maximum bankfull side slope	2.5(H):1(V)
Minimum radius of curvature	2.5 times top width

[1] Roughly equivalent to a 1.5-year event based on extrapolation of regional data.

6.0 Swales

The functions and benefits of natural streams can be extended further upstream in the watershed by conveying runoff on the surface in vegetated channels and swales rather than in underground storm drains. Besides the aesthetic and habitat value of surface channels, stormwater quality can be enhanced by promoting beneficial interaction between water, soil, and vegetation. Conveyance in storm drains produces no such interaction or water quality enhancement.

Guidance is provided in this subsection for the design of swales, draining areas from less than an acre up to about 10 impervious acres (e.g., 20 acres at 50% imperviousness). A series of design charts are provided to guide the designer in determining stable conditions in vegetated or void-filled riprap swales of varying cross sections based on design flow rate and slope. The charts show flow rates as high as 100 cfs (stable at relatively flat slopes) and slopes as steep as 10 percent (stable at relatively low flows). It should be noted that the design criteria in this section differs from those in *Volume 3* of this manual. Volume 3 criteria are intended to provide a higher level of water quality treatment. These criteria are intended for stable conveyance more so than water quality benefits.

6.1 Design Criteria for Swales

Design criteria are described for grass and rock (soil riprap or void-filled riprap) swales. Where indicated by Figures 8-22 through 8-25, grass swales meeting these criteria are preferred, but when conditions require, swales lined with soil riprap or void-filled riprap are advisable.

In order to maximize the use of grass swales, and increase the likelihood that the swale will remain functional and stable over time, two key design principles should be considered.

1. **Adopt shallow swale section with flat bottom.** Swale cross sections that allow runoff to spread out (shallow, flat bottom with gentle side slopes) promote lower velocities and shear stresses than triangular (or “V” shaped) swales. This is also good for water quality. In general, the wider the bottom width of the swale, the more stable it will be, although concentrated flow paths may still form. It is generally recommended that swales be of a trapezoidal shape with a bottom width of 2 feet or more and with side slopes that are 5:1 or flatter.

2. **Establish dense turf-forming grass in suitable soils**. The single most important factor in creating stable grass swales is to establish a dense stand of turf-forming grass in the bottom and side slopes of the swale. This requires good soils or amendments and proper soil preparation and planting. Irrigation may also be necessary. See the *Revegetation* chapter for more information.

6.1.1 Stability Charts

Swale stability based on slope, flow rate, swale geometry, and grass or rock lining are shown graphically in Figures 8-22 through 8-25. Design guidance is provided in the stability charts for design discharges up to 100 cfs and for longitudinal slopes up to 10 percent. Although these figures go up to 100 cfs, it may be appropriate to design a more naturalized channel section for flow rates greater than 30 to 40 cfs. This is largely dependent on site-specific considerations. As already mentioned, steep swales are most feasible for small discharges while swales carrying large discharges are most feasible at flatter slopes. If the chart is indicating that riprap greater than Type H (see Figure 8-34) is required, a swale for those hydraulic conditions is not recommended. Typically, if Type H riprap is required, consider other options such as widening the swale or flattening the slope.

The use of Figures 8-22 through 8-25 for swale stability analysis requires that the geometric parameters indicated at the top of each chart apply and the requirements of Section 6.2 for grass swales and Section 6.3 for soil riprap or void-filled riprap are met.

Table 8-4 below summarizes the appropriate stability chart to reference based upon the swale geometry.

Table 8-4. Summary of swale properties for stability chart reference

Bottom Width	Side slope	Stability Chart
2 - 4 feet	between 5:1 and 10:1	Figure 8-22
2 - 4 feet	10:1 or flatter	Figure 8-23
greater than 4 feet	between 5:1 and 10:1	Figure 8-24
greater than 4 feet	10:1 or flatter	Figure 8-25

For swales outside the range of application of Figures 8-22 through 8-25, specific analysis of the proposed swale parameters may be required. See Section 6.2 for additional guidance on determining the stability of grass swales. Analysis for riprap-lined swales should be completed using the methodologies discussed in Section 6.3.

6.2 Grass Swales

6.2.1 Soil and Vegetation Properties

The single most important factor governing the stability of grass swales is the quality of vegetation. Refer to the *Revegetation* chapter of this manual for proper site preparation including soil testing, topsoil, amendments, and recommendations for addressing soil compaction. The *Revegetation* chapter also provides recommended seed mixes. Turf-forming grasses that include a variety of species work best.

In addition to seeding, it is recommended that grass plugs of the dominant species in the seed mix be planted to provide some immediate vegetative cover and improve overall establishment. Place drier species on the side slopes. Placing sod is also an option for grass swales.

Discussion regarding the use of Handbook #667 for stability analysis of grass channels can be found in Section 4.7.

6.2.2 Construction

It is imperative that the construction drawings and specifications address seedbed preparation; installation of seed, blankets, and plugs; temporary irrigation; weed control; and follow-up reseeding and maintenance. Specific construction recommendations, including for submittals and inspections, can be found in the *Revegetation* chapter. Good temporary erosion controls are critical during establishment of vegetation.

6.3 Soil Riprap and Void-Filled Riprap Swales

For swales that require riprap lining, use a soil riprap for void-filled riprap mix. Additional information is provided in Section 8.0. Use Figures 8-22 through 8-25 for final design only when the appropriate geometric parameters are met. Table 8-4 summarizes the appropriate stability chart based on swale geometry.

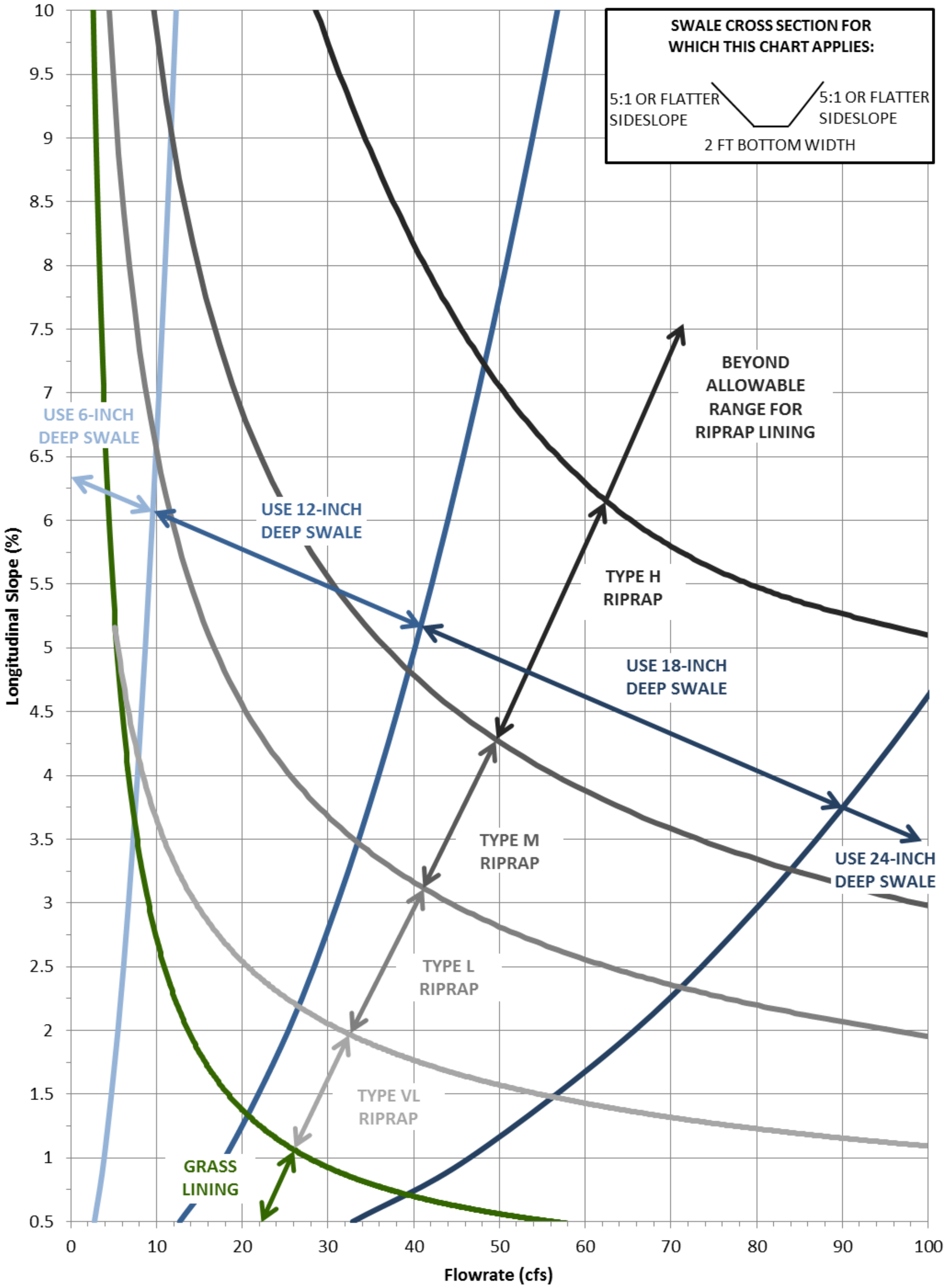


Figure 8-22. Swale stability chart; 2- to 4-foot bottom width and side slopes between 5:1 and 10:1
(Note: Riprap classifications refer to gradation for riprap used in soil riprap or void-filled riprap. See Figure 8-34 for gradations.) (Source: Muller Engineering Company)

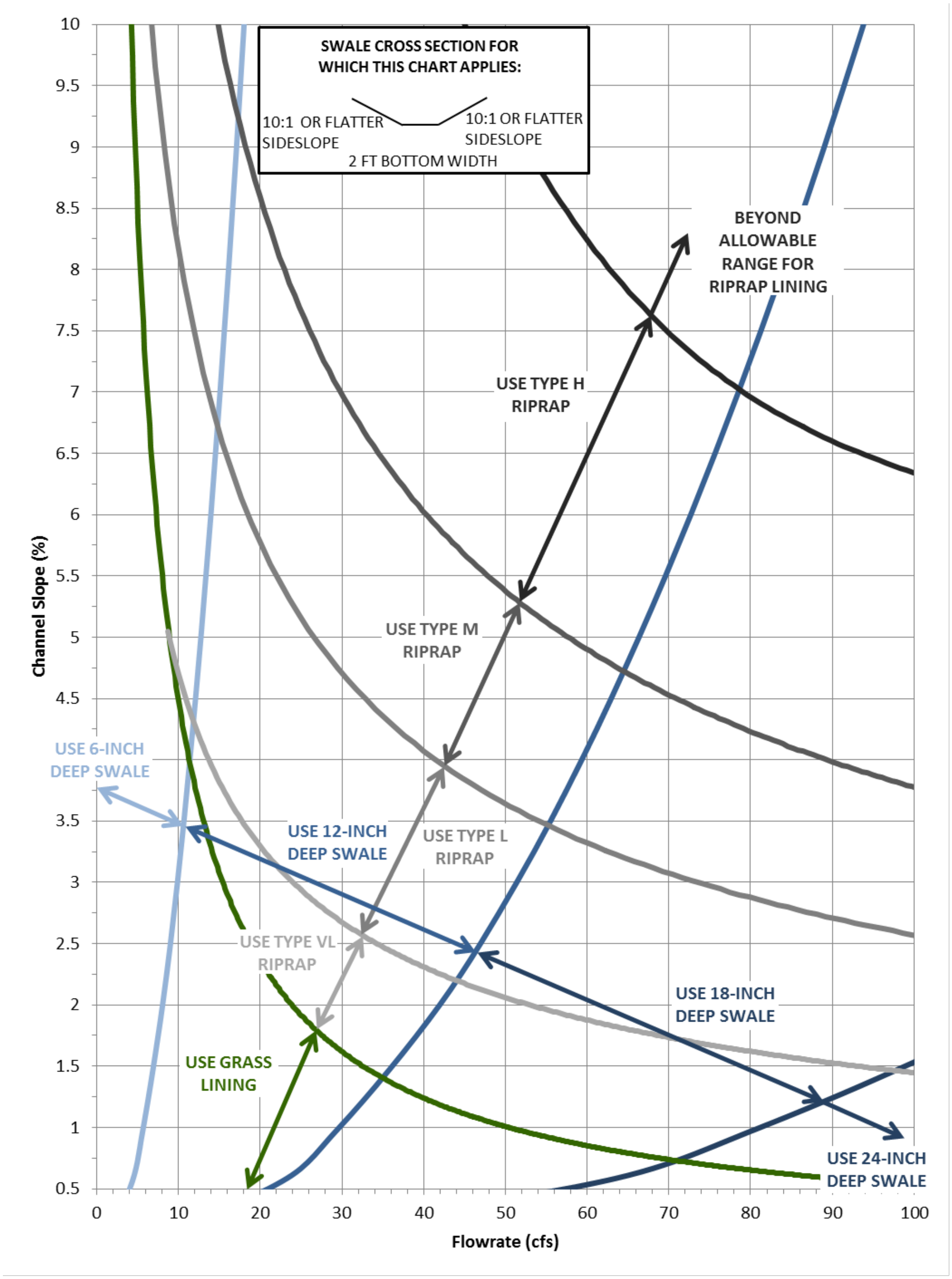


Figure 8-23. Swale stability chart: 2- to 4-foot bottom width and 10:1 (or flatter) side slopes
(Note: Riprap classifications refer to gradation for riprap used in soil riprap or void-filled riprap. See Figure 8-34 for gradations.) (Source: Muller Engineering Company)

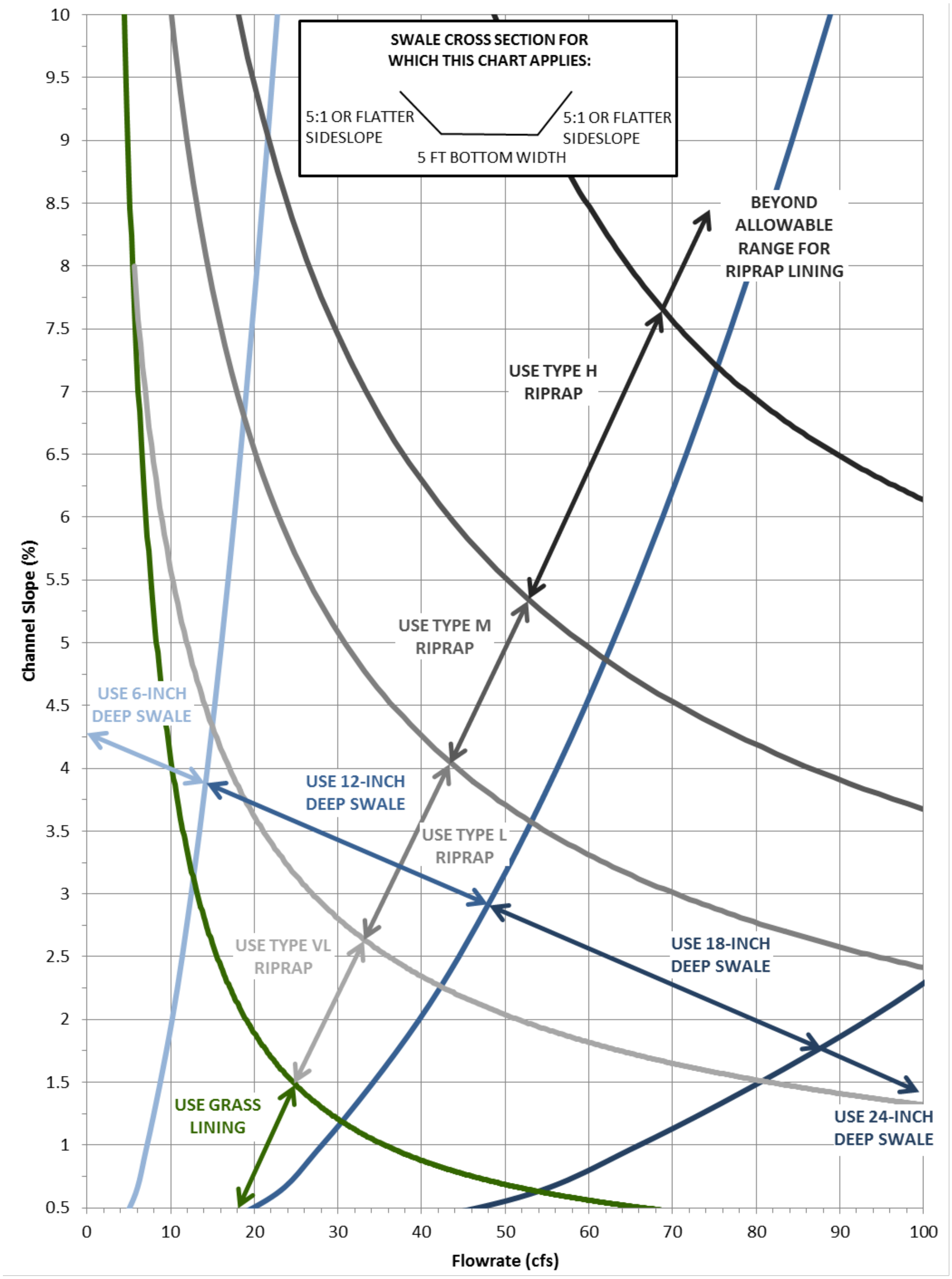


Figure 8-24. Swale stability chart: greater than 4-foot bottom width and side slopes between 5:1 and 10:1

(Note: Riprap classifications refer to gradation for riprap used in soil riprap or void-filled riprap. See Figure 8-34 for gradations.) (Source: Muller Engineering Company)

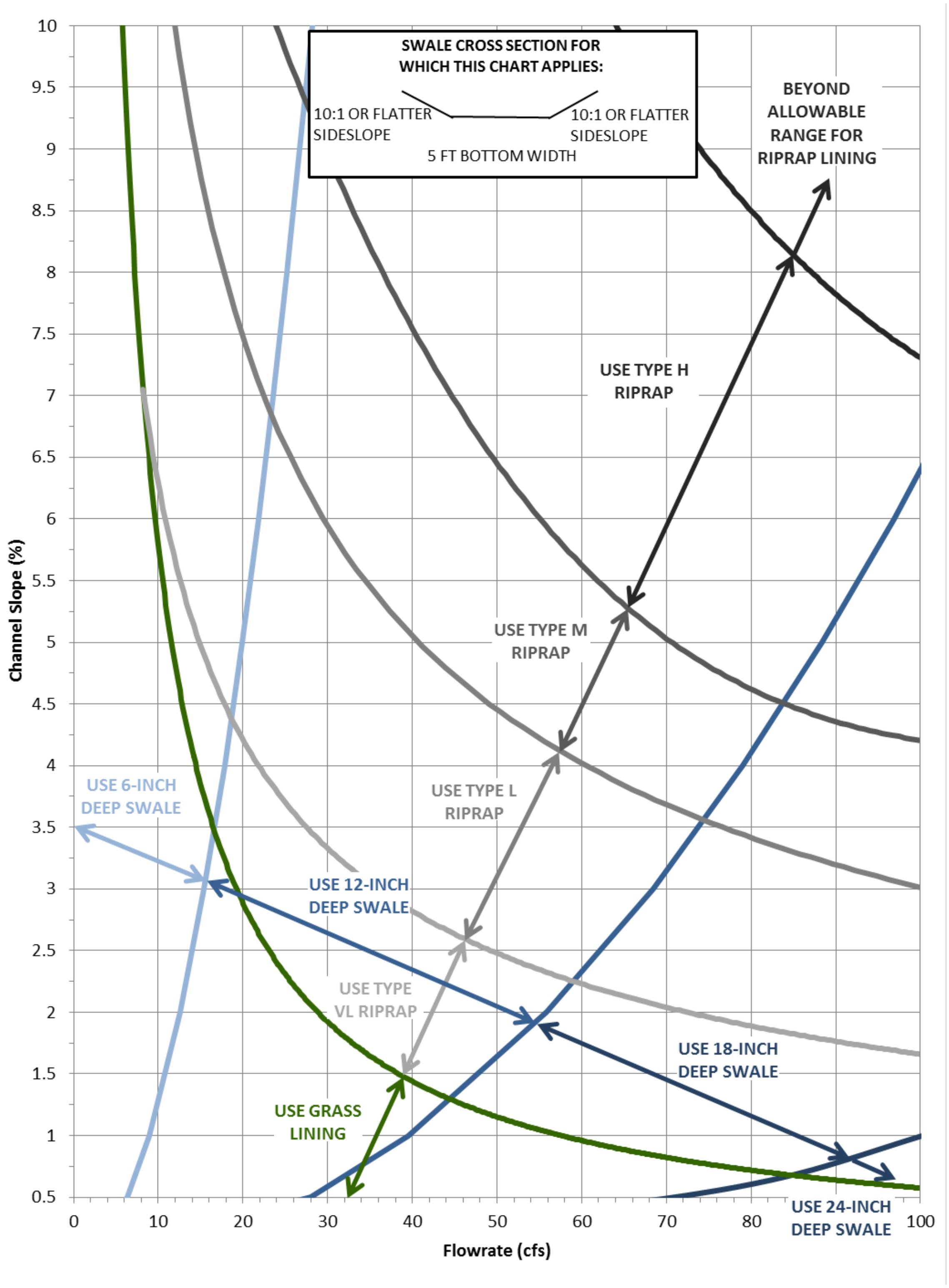


Figure 8-25. Swale stability chart: greater than 4-foot bottom width and 10:1 (or flatter) side slopes
(Note: Riprap classifications refer to gradation for riprap used in soil riprap or void-filled riprap. See Figure 8-34 for gradations.) (Source: Muller Engineering Company)

7.0 Hydraulic Analysis

Evaluating channel and floodplain hydraulics is a key component of any stream project. Hydraulic modeling provides insight into flow properties including water surface elevation, depth, velocity, shear stress, and Froude Number. Understanding these flow properties is necessary to assess risks associated with structure flooding and channel erosion and can help guide the design of stream capacity and stabilization improvements.

7.1 Preliminary Channel Analysis

For detailed hydraulic analysis, hydraulic modeling software is recommended (i.e., HEC-RAS). There may be times when a preliminary or “quick” analysis is needed to evaluate channel properties in uniform steady flow conditions. For these cases, Manning’s Equation should be used. Manning’s Equation describes the relationship between channel geometry, slope, roughness and discharge for uniform flow conditions and is expressed as:

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \qquad \text{Equation 8-6}$$

Where:

Q = discharge (cfs)

n = roughness coefficient (see Section 7.2.3)

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

R = hydraulic radius = A/P (ft)

P = wetted perimeter (ft)

S = friction slope (ft/ft) (approximated by channel invert slope for normal depth calculations)

Manning's Equation can also be expressed in terms of velocity by employing the continuity equation, $Q = VA$, as a substitution in Equation 8-6, 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:

$$Q = \frac{1.49}{n} b y^{5/3} S^{1/2} \qquad \text{Equation 8-7}$$

The solution of Equation 8-6 for depth is iterative, therefore using a software program to assist with this calculation can be beneficial. A number of additional software packages are available to solve Manning’s Equation by inputting known channel properties.

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 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 the hydraulic conditions that will actually occur.

7.2 HEC-RAS Modeling

The most commonly used tool for open channel hydraulic modeling is the Hydrologic Engineering Center's River Analysis System (HEC-RAS) from the US Army Corps of Engineers. For the purpose of this chapter, discussion will focus on HEC-RAS's ability to perform one-dimensional steady flow analysis using a series of input parameters. Typical input parameters include flowrate, channel cross section geometry, roughness coefficients, main channel bank stations, etc. HEC-RAS has the capability to model bridges, culverts, weirs and spillways as well as address unsteady flow computations. In most cases, a subcritical HEC-RAS run is appropriate for natural channels since significant reaches of supercritical flow do not often occur in natural Front Range streams (Jarrett 1985). This section provides guidance on determining appropriate input parameters and reviewing output information when undertaking HEC-RAS modeling.

7.2.1 Cross Section Location

Cross sections should be placed relatively frequently along a channel reach in order to adequately evaluate the channel characteristics. Cross section placement should be governed by changes in discharge, channel width, slope, shape, roughness, and the location of hydraulic structures (bridge, culvert, grade control structure, etc.). Typical cross section spacing may be in the range of 200 to 400 feet or closer if conditions warrant. Refer to the *Hydraulic Structures* chapter and the *Culverts and Bridges* chapter guidance on cross section placement for grade control structures and bridges respectively. The HEC-RAS Hydraulic Reference Manual is an essential document to be familiar with when performing HEC-RAS analyses.

In addition to spacing of cross sections along a stream reach, the designer must consider the alignment of individual cross sections. Cross section should generally be oriented to be perpendicular to the channel centerline and the water flow path. At times it may be necessary to include deflections in the cross section in order to be perpendicular to flow in the channel terraces. Figure 8-26 illustrates an example of cross section placement and alignment to capture channel flow paths perpendicular to the cross section.

2D Flow Modeling

Two-dimensional hydraulic modeling is not addressed in this manual, although its use is becoming more widespread for evaluating complex hydraulic conditions. Guidance in this manual is limited to one-dimensional modeling using HEC-RAS. This is the primary tool for modeling stream restoration improvements.

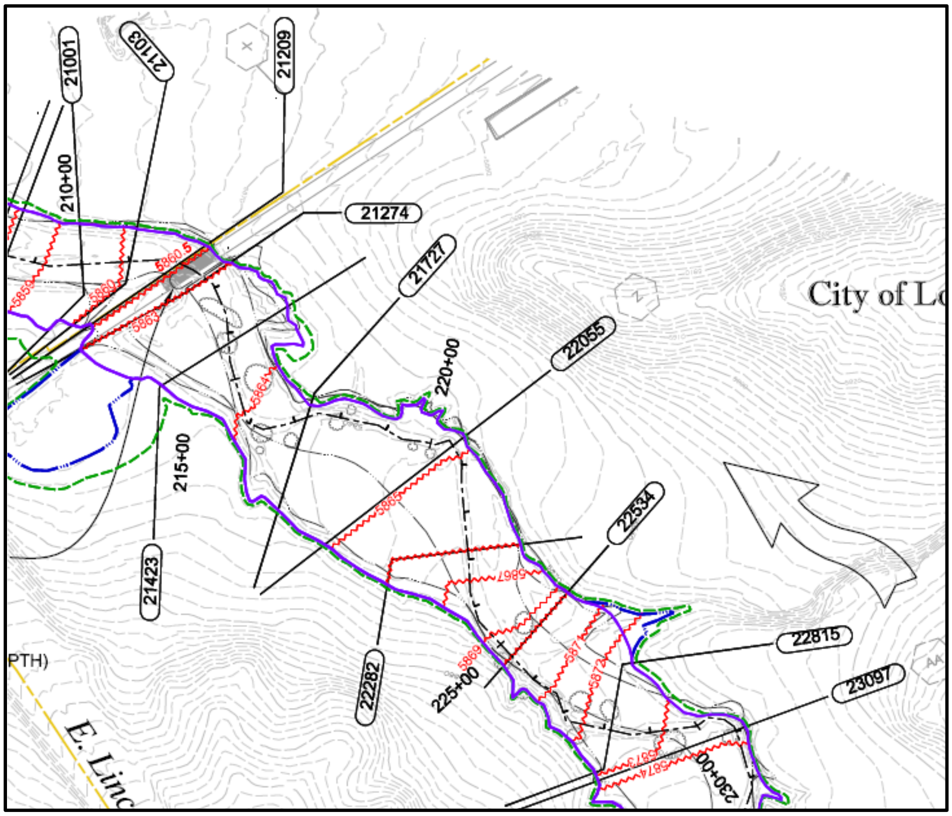


Figure 8-26. Example of HEC-RAS cross section placement and alignment

7.2.2 Cross Section Geometry

Required cross section input data includes station (x) and elevation (y) coordinates of the cross section, main channel bank stations, roughness coefficients, and contraction/expansion coefficients.

Cross Section Coordinates and Main Channel Bank Stations

Entering cross section coordinates can be accomplished in several different ways. There are several software packages that can generate cross section data from a digital terrain model and import it directly. Cross sections can also be entered manually. Regardless of the method, it is critical that the input coordinates accurately represent the horizontal and vertical geometry of cross sections, so back-checking for quality assurance is recommended.

Once the station and elevation coordinates for the channel cross section have been input into HEC-RAS, the main channel bank stations must be determined. It is generally recommended that the main channel be interpreted as a relatively narrow portion of the cross section. Figure 8-27 illustrates the main channel and terraces in a typical cross section. The bankfull channel comprises the deepest part of the cross section, often has a lower roughness value than the vegetated terraces, and typically experiences the highest flow velocities. Sometimes, small headwater channels and especially swales may have a vegetated bankfull channel as a result of minimal or no baseflow.

Required input for HEC-RAS includes reach lengths to the next downstream cross section. The downstream reach length for the main channel is measured along the established channel centerline. The downstream reach lengths for the left and right overbank is measured following the flowpath of water in the overbanks from the centroid of flow in the overbank of one cross section to the centroid of flow in the next section downstream. This means that the overbank distance on the inside of the bend will be less than the overbank distance on the outside of the bend.

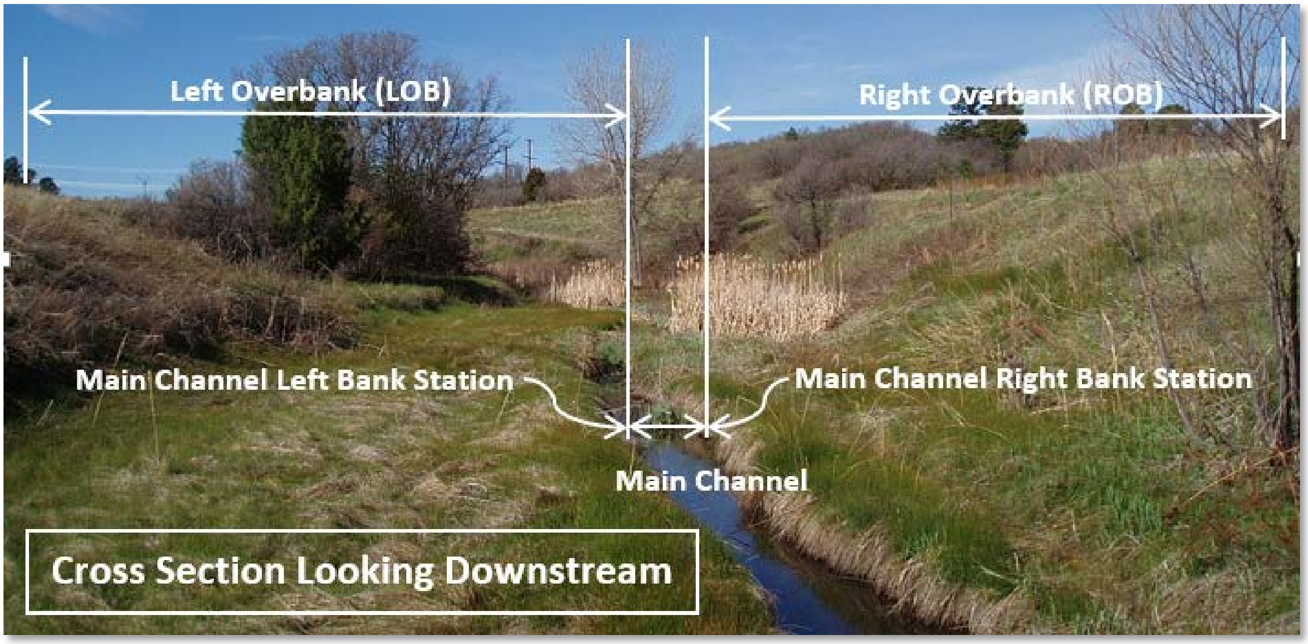


Figure 8-27. HEC-RAS cross section definitions

7.2.3 Roughness Coefficients

Required input also includes defining hydraulic roughness coefficients, or Manning's n values, for the main channel, left overbank and right overbank. For channel cross sections that are best described with varying values for Manning's n in the overbanks, the "Horizontal Variation in n Values" feature can be used. This feature allows the designer to specify a Manning's n value at each cross section coordinate.

Selecting roughness values for the main channel and overbanks of each cross section in the model is an important task. Because this tends to be somewhat subjective rather than deterministic, it is recommended that hydraulic modeling be conducted in two ways. Conservatively low roughness values should be used for assessing velocities, Froude numbers, and shear stresses. Conservatively high roughness values should be used for assessing water surface elevations and depths. The lack of vegetation in post construction conditions will result in higher channel velocities and greater potential for erosion. Channels with fully established vegetation will have reduced velocities but higher flow depths.

Table 8-5 provides low and high roughness values that are suitable for initial approximations of hydraulic conditions; however, it is the designer's responsibility to conduct a field reconnaissance of the stream reach being analyzed, characterize roughness conditions along the main channel and overbanks, and select appropriate roughness values. Additional information on estimating roughness values for grass overbanks and cobble channels is discussed below.

Table 8-5. Recommended roughness values

Location and Cover	**When Assessing Velocity, Froude No., Shear Stress**	**When Assessing Water Surface Elevation and Water Depth**
Main Channel (bankfull channel)		
Sand or clay bed	0.03	0.04
Gravel or cobble bed	0.035	0.07
Vegetated Overbanks		
Turfgrass sod	0.03	0.04
Native grasses	0.032	0.05
Herbaceous wetlands (few or no willows)	0.06	0.12
Willow stands, woody shrubs	0.07	0.16

(Source: Chow 1959, USDA 1954, Barnes 1967, Arcement and Schneider 1989, Jarrett 1985)

Roughness of Grass Overbanks

A common procedure for determining Manning’s n for vegetated channels is documented in the *Handbook of Channel Design for Soil and Water Conservation* (hereinafter referred to as the NRCS Method). The NRCS Method uses the vegetation properties to establish a degree of retardance. The retardance is based upon the type of plants, the length and condition of the vegetation. Finding a solution for Manning’s n becomes an iterative process using the following channel properties: slope, velocity and hydraulic radius. The documentation for the NRCS method contains a series of curves that provide solutions for Manning’s n values based upon the vegetation retardance. Table 8-6 provides recommended retardance values for channels located along the Colorado Front Range with the given vegetation properties. Refer to the NRCS Method documentation for additional detail and guidance.

Table 8-6. Recommended retardance curve for vegetation in the Colorado Front Range

Vegetation Description	Retardance Curve
Fair Stand	
≤8" height	E
>8" height	D
Good Stand	
≤8" height	D
>8" height	C
Dense, Herbaceous Wetland	A

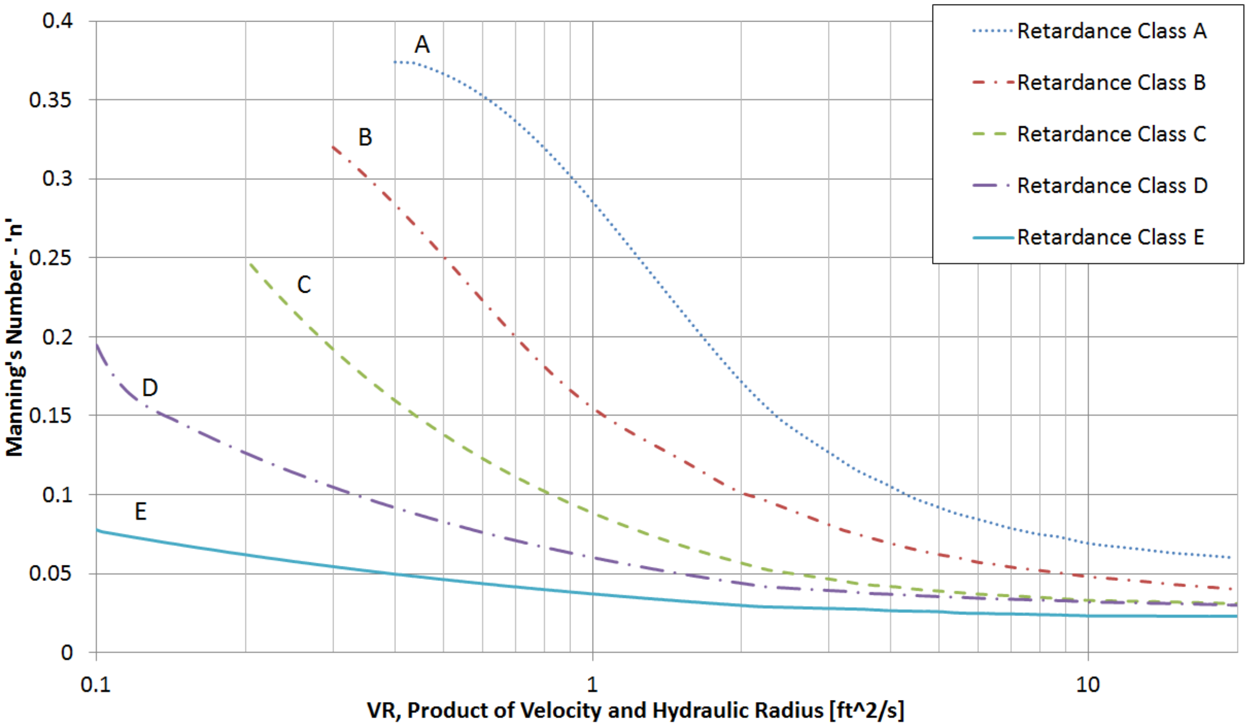


Figure 8-28. Manning's roughness in vegetated channels

Roughness of Cobble (Rock) Channels and Riprap Areas

There are multiple methods available for determining Manning's n values for cobble/rock lined channels and significant areas of riprap. Two relationships are shown below; it is the responsibility of the designer to evaluate the methods available and determine the approach most appropriate for the specific project conditions.

Determination of Roughness Coefficients for Streams in Colorado (Jarrett 1985)

$$n = 0.39S^{0.38}R^{-0.16}$$ Equation 8-8

Where:

S = channel slope (ft/ft)

R = hydraulic radius (ft)

The Manning's roughness coefficient, *n*, for a void-filled or soil riprap-lined channel may be estimated using:

$$n = 0.0395D_{50}^{1/6}$$ Equation 8-9

Where:

D_{50} = mean stone size (feet)

This equation is appropriate for computing channel capacity and associated flow depth, but when soil riprap is vegetated, velocity and shear computations should be based on the roughness provided by the vegetation and not the riprap.

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 this equation. The *Hydraulic Structures* chapter covers grouted boulder applications in detail.

7.2.4 Design Storms

HEC-RAS refers to design storms as "profiles" and allows a designer to add multiple profiles. Boundary conditions are defined for each profile and options consist of known water surface elevation, critical depth, normal depth or rating curve.

It is recommended that the designer evaluate multiple return periods (profiles) when evaluating a stream reach. These may include the "bankfull" event, 2-year, 5-year, 10-year, 100-year, and perhaps larger events. The 2 through 10-year profiles are important when a shared-use path is planned adjacent to the stream to ensure proper elevation of the past. See the *Stream Access and Recreational Channels* chapter for criteria regarding trails including low-flow crossings.

Evaluation of multiple design storms allows the designer to see variations in flow patterns for different storm events and the resulting velocities, flow depths, etc. In some cases it may be appropriate to modify Manning's n values based on the flow depth at a specific design storm to more accurately depict the flow conditions.

7.2.5 Output Variables

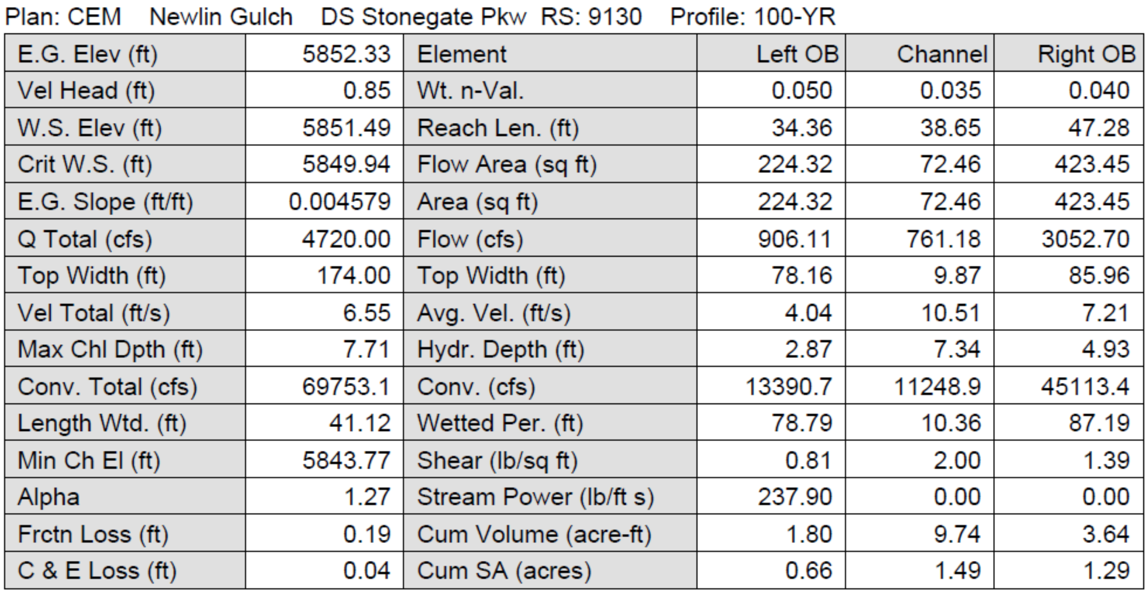
Results from a HEC-RAS steady flow analysis can be viewed in both tabular and graphical format. Tabular output can be generated at an individual cross section or a summary table can be produced that includes multiple cross sections and multiple storm events (profiles). The following is a list of key output variables that the designer should review during analysis (abbreviations used by HEC-RAS are indicated in parentheses).

- Water surface elevation (W.S. Elev)
- Critical water surface elevation (Crit W.S.)
- Froude Number (Froude #)
- Total flowrate within the cross section (Q Total), left overbank (Q Left), channel (Q Channel), and right overbank (Q Right)
- Average velocity in the main channel (Vel Chnl), left overbank (Vel Left), and right overbank (Vel Right)
- Hydraulic depth in the main channel (Hydr Depth C), left overbank (Hydr Depth L), and right overbank (Hydr Depth R)
- Specific Force for the cross section (Specif Force)
- Shear stress in the main channel (Shear Chan), left overbank (Shear LOB), and right overbank (Shear ROB)

The above list is just a small sampling of the variables that HEC-RAS can provide. The designer is responsible for selecting output variables, evaluating all aspects of the channel hydraulics, and determining the acceptable values for the channel parameters based upon the specific project.

Figure 8-29 is an example of tabular output for an individual cross section (referred to as *Detailed Output Table*). Data are provided for the entire cross section and also divided into the bankfull channel and the left/right overbanks, where appropriate.

In addition to the table for an individual cross section, HEC-RAS can also provide a summary table which includes all cross sections and all storm events (profiles) as specified (referred to as *Profile Output Table*). When using the *Profile Output Table* feature, the designer has the ability to create a custom table and specify the output variables that are included in the table, including those listed above. Creating a custom table in HEC-RAS is a useful way to see all of the data summarized at one location. Refer to the *Help* menu, *User's Manual* within HEC-RAS for definitions of the output variables available within HEC-RAS.

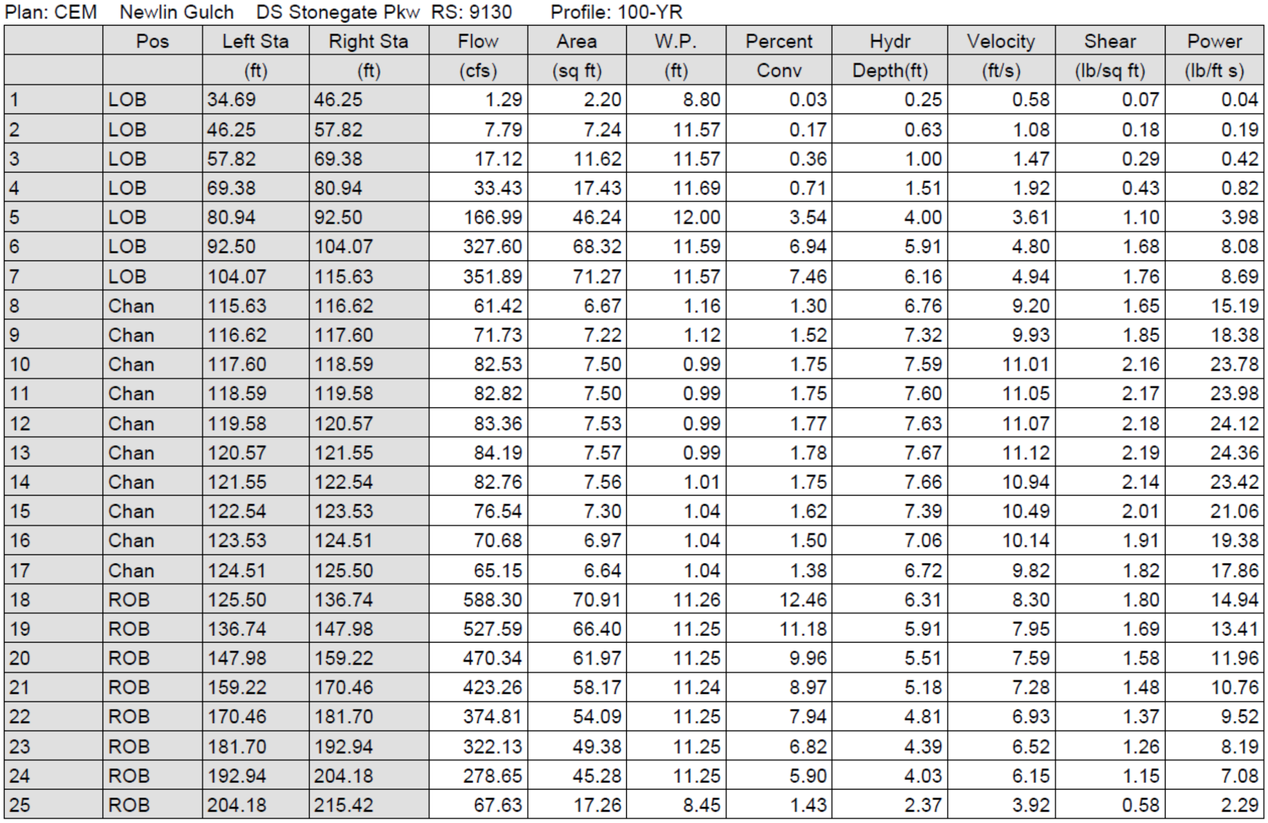


Plan: CEM Newlin Gulch DS Stonegate Pkw RS: 9130 Profile: 100-YR

E.G. Elev (ft)	5852.33	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.85	Wt. n-Val.	0.050	0.035	0.040
W.S. Elev (ft)	5851.49	Reach Len. (ft)	34.36	38.65	47.28
Crit W.S. (ft)	5849.94	Flow Area (sq ft)	224.32	72.46	423.45
E.G. Slope (ft/ft)	0.004579	Area (sq ft)	224.32	72.46	423.45
Q Total (cfs)	4720.00	Flow (cfs)	906.11	761.18	3052.70
Top Width (ft)	174.00	Top Width (ft)	78.16	9.87	85.96
Vel Total (ft/s)	6.55	Avg. Vel. (ft/s)	4.04	10.51	7.21
Max Chl Dpth (ft)	7.71	Hydr. Depth (ft)	2.87	7.34	4.93
Conv. Total (cfs)	69753.1	Conv. (cfs)	13390.7	11248.9	45113.4
Length Wtd. (ft)	41.12	Wetted Per. (ft)	78.79	10.36	87.19
Min Ch El (ft)	5843.77	Shear (lb/sq ft)	0.81	2.00	1.39
Alpha	1.27	Stream Power (lb/ft s)	237.90	0.00	0.00
Frctn Loss (ft)	0.19	Cum Volume (acre-ft)	1.80	9.74	3.64
C & E Loss (ft)	0.04	Cum SA (acres)	0.66	1.49	1.29

Figure 8-29. Example HEC-RAS tabular output for individual cross section

When performing a steady flow analysis with HEC-RAS, the user has the option to evaluate flow distribution at one or more cross section. The user can specify the interval of the distribution (e.g., every 10 feet along cross section or at other intervals) and then use the results to evaluate hydraulic parameters at specific locations on a cross section. This may be beneficial when determining erosion protection at the toe of the bankfull channel versus a location in the overbank. The designer can review the flow velocity at that specific location in the cross section and determine the appropriate erosion protection. Figure 8-30 is an example table summarizing the flow distribution at an individual cross section.



Plan: CEM Newlin Gulch DS Stonegate Pkw RS: 9130 Profile: 100-YR

	Pos	Left Sta (ft)	Right Sta (ft)	Flow (cfs)	Area (sq ft)	W.P. (ft)	Percent Conv	Hydr Depth(ft)	Velocity (ft/s)	Shear (lb/sq ft)	Power (lb/ft s)
1	LOB	34.69	46.25	1.29	2.20	8.80	0.03	0.25	0.58	0.07	0.04
2	LOB	46.25	57.82	7.79	7.24	11.57	0.17	0.63	1.08	0.18	0.19
3	LOB	57.82	69.38	17.12	11.62	11.57	0.36	1.00	1.47	0.29	0.42
4	LOB	69.38	80.94	33.43	17.43	11.69	0.71	1.51	1.92	0.43	0.82
5	LOB	80.94	92.50	166.99	46.24	12.00	3.54	4.00	3.61	1.10	3.98
6	LOB	92.50	104.07	327.60	68.32	11.59	6.94	5.91	4.80	1.68	8.08
7	LOB	104.07	115.63	351.89	71.27	11.57	7.46	6.16	4.94	1.76	8.69
8	Chan	115.63	116.62	61.42	6.67	1.16	1.30	6.76	9.20	1.65	15.19
9	Chan	116.62	117.60	71.73	7.22	1.12	1.52	7.32	9.93	1.85	18.38
10	Chan	117.60	118.59	82.53	7.50	0.99	1.75	7.59	11.01	2.16	23.78
11	Chan	118.59	119.58	82.82	7.50	0.99	1.75	7.60	11.05	2.17	23.98
12	Chan	119.58	120.57	83.36	7.53	0.99	1.77	7.63	11.07	2.18	24.12
13	Chan	120.57	121.55	84.19	7.57	0.99	1.78	7.67	11.12	2.19	24.36
14	Chan	121.55	122.54	82.76	7.56	1.01	1.75	7.66	10.94	2.14	23.42
15	Chan	122.54	123.53	76.54	7.30	1.04	1.62	7.39	10.49	2.01	21.06
16	Chan	123.53	124.51	70.68	6.97	1.04	1.50	7.06	10.14	1.91	19.38
17	Chan	124.51	125.50	65.15	6.64	1.04	1.38	6.72	9.82	1.82	17.86
18	ROB	125.50	136.74	588.30	70.91	11.26	12.46	6.31	8.30	1.80	14.94
19	ROB	136.74	147.98	527.59	66.40	11.25	11.18	5.91	7.95	1.69	13.41
20	ROB	147.98	159.22	470.34	61.97	11.25	9.96	5.51	7.59	1.58	11.96
21	ROB	159.22	170.46	423.26	58.17	11.24	8.97	5.18	7.28	1.48	10.76
22	ROB	170.46	181.70	374.81	54.09	11.25	7.94	4.81	6.93	1.37	9.52
23	ROB	181.70	192.94	322.13	49.38	11.25	6.82	4.39	6.52	1.26	8.19
24	ROB	192.94	204.18	278.65	45.28	11.25	5.90	4.03	6.15	1.15	7.08
25	ROB	204.18	215.42	67.63	17.26	8.45	1.43	2.37	3.92	0.58	2.29

Figure 8-30. Example HEC-RAS tabular output for flow distribution at individual cross section

Graphical output can be in the form of a cross section, water surface profile, or rating curve. The user has the ability to specify the variables that are included on the graphical output. Figure 8-31 is an example plot of a cross section showing a velocity distribution. The velocity distribution is generated by turning on the flow distribution feature of HEC-RAS, as discussed earlier in this section.

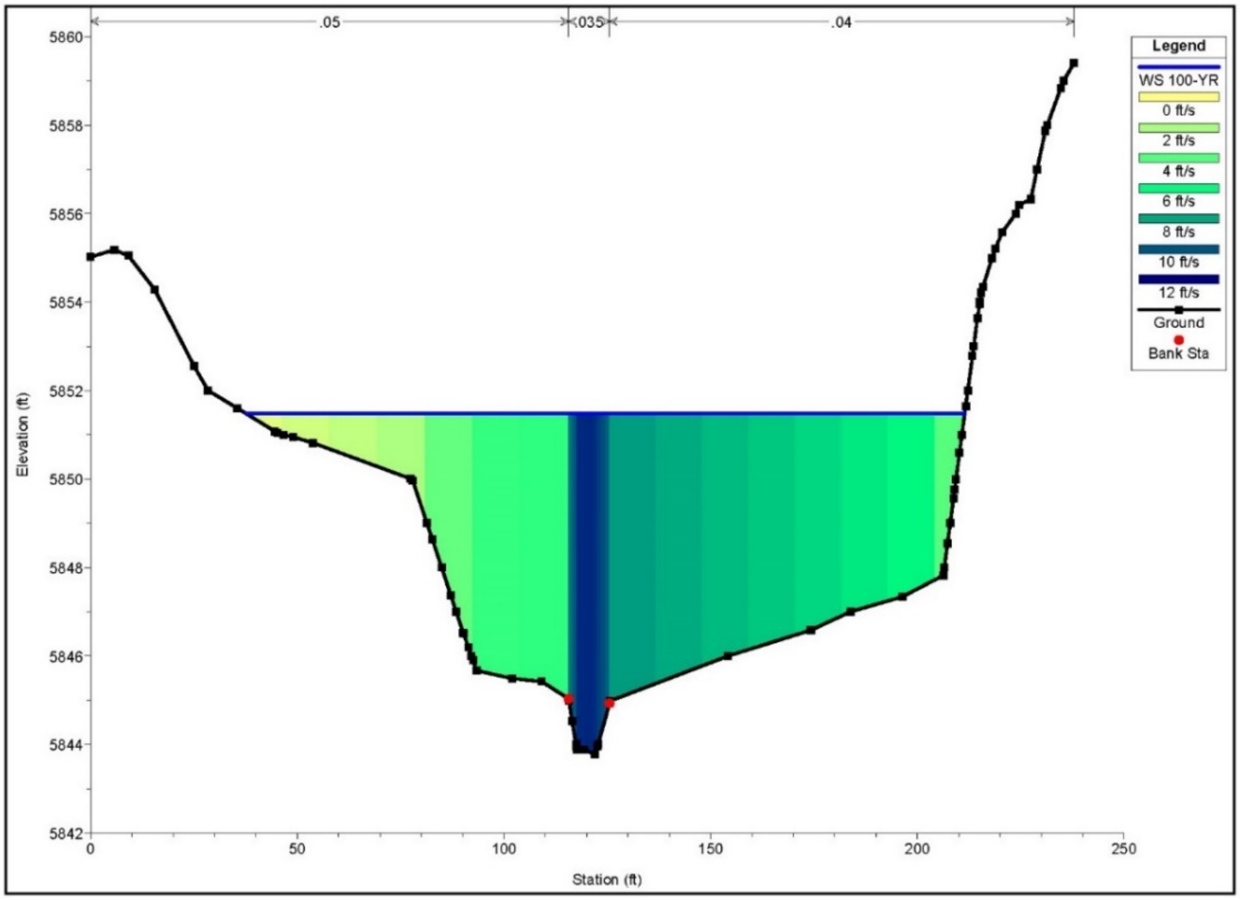


Figure 8-31. Example HEC-RAS cross section with velocity distribution

Using the *General Profile Plot* feature of HEC-RAS, multiple variables can be viewed in a profile format along the length of a stream. An example plot using this feature is shown in Figure 8-32 below. Figure 8-32 is a plot of shear stress for a channel reach which separates the output into the main channel, left overbank and right overbank.

The example plot indicates that overbank shear stress is highest near stations 200, 900, 1800 and extremely high near station 2600. The information shown in the figure would lead the designer to assess the ability of the overbank vegetation to resist the imposed shear in these stations. If the shear stress is greater than the estimated ability of the overbank to resist, the designer should assess the associated risks and consider whether steps should be taken to reinforce the overbank at these locations.

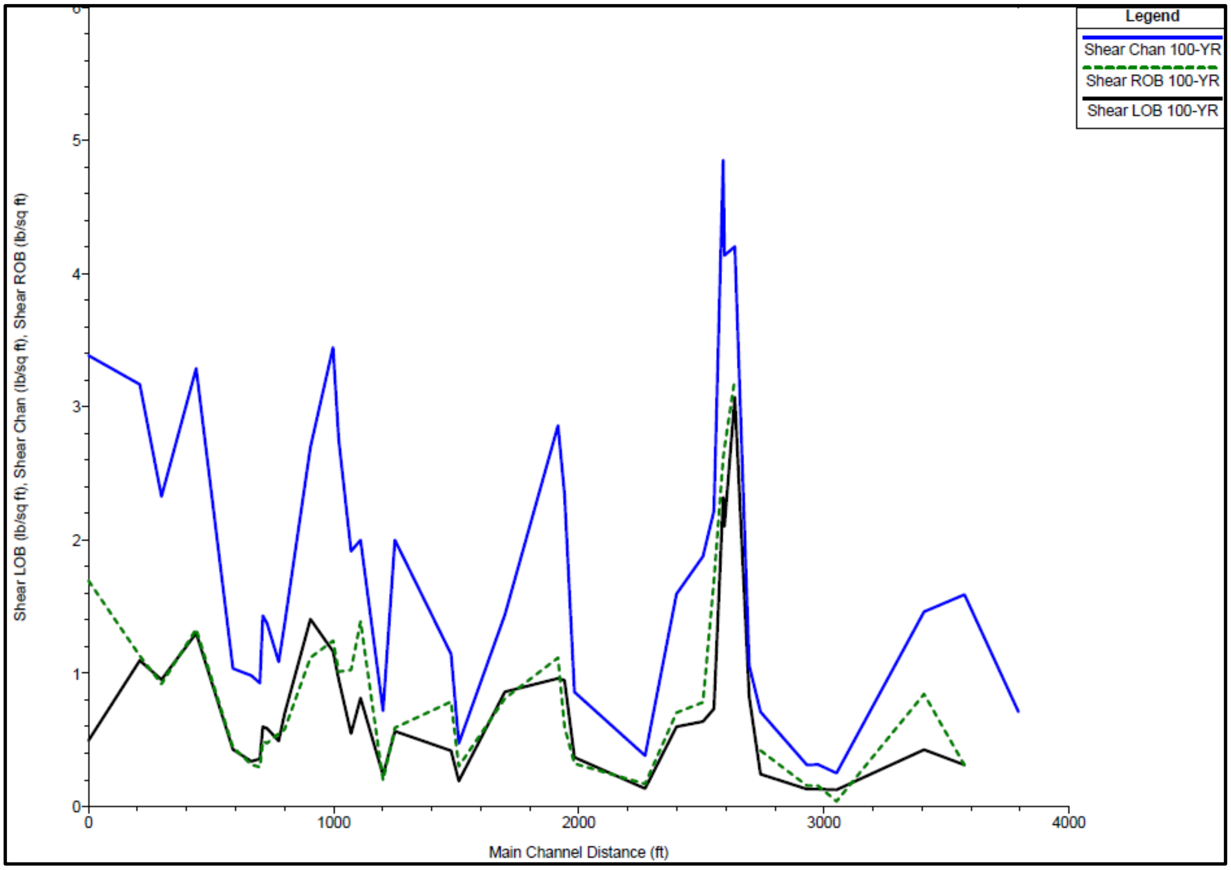


Figure 8-32. Example HEC-RAS general profile plot of shear stress

7.3 Evaluation of Erosion at Channel Bends

Special erosion control measures are often needed at bends. Riprap sizing should be based on locally higher velocities at the outside of a bend. An estimate of velocity along the outside of the bend can to be made using the following equation.

$$V_a = (-0.147\frac{r_c}{T} + 2.176)V \qquad \text{Equation 8-10}$$

Where:

V_a = adjusted channel velocity for riprap sizing along the outside of channel bends (ft/sec)

V = mean channel velocity for the peak flow of the major design flow (ft/sec)

r_c = channel centerline radius (ft)

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

8.0 Rock and Boulders

In conditions where rock protection is required, it is recommended that soil riprap, void-filled riprap, or boulders be used. For small installations, and where vegetation is not anticipated, riprap over bedding material may also be used.

Soil riprap refers to riprap that has all void spaces filled with topsoil with the intention of supporting vegetative growth. Soil riprap is intended for use in applications where vegetative cover can be established and where the shear stress, imposed by frequently occurring flows, is less than the resistive strength of the vegetation and soil. The riprap layer is designed to remain stable and provide protection during the extreme events.

Void-filled riprap is designed to emulate natural rock riffle material found in steep gradient streams. It contains a well-graded mix of cobbles, gravels, sands, and soil that fills all voids and acts as an internal filter, therefore a separate bedding layer between subgrade and rock is not required. In applications where it is difficult to establish vegetation, void-filled riprap is better able to resist the direct, prolonged impingement of water on the riprap installation compared to soil riprap. However, void-filled riprap is more difficult to properly mix and install compared to soil riprap (see inset). UDFCD recommends review of the technical paper titled d*emonstration Project Illustrating Void-Filled Riprap Applications in Stream Restoration* (Wulliman and Johns 2011). This paper provides background on the derivation of void-filled riprap and its applications in stream restoration and is available the UDFCD website.

Photograph 8-18. Void-filled riprap is designed to emulate natural rock riffle material; it consists of a mix of rock, gravels, sands, and soil that is densely-packed and able to support riparian vegetation.

Table 8-7 provides a comparison between soil riprap and void-filled riprap.

Specifying Void-Filled Riprap

Void-filled riprap is far more challenging to properly mix and install than soil riprap and requires close designer involvement during construction to ensure the mixture is properly mixed and placed. When it is not properly mixed and/or placed, flows will wash away the void material and eventually start to also move the larger rock. Before specifying void-filled riprap, ensure that adequate construction observation time by a qualified individual is available as part of the construction budget. For more information on mixing and placing void-filled riprap see the technical paper titled *Demonstration Project Illustrating Void-Filled Riprap Applications in Stream Restoration* (Wulliman and Johns 2011) and the UDFCD construction specifications, both available at www.UDFCD.org.

Table 8-7. Comparison of void-filled riprap and soil riprap

	Void-Filled Riprap	Soil Riprap
Advantages	▪ Better emulates natural streambed material. ▪ Provides better stability and armoring in riverine environments. ▪ Creates a dense, interlocking mass and functions as an effective internal filter, keeping water flows on the surface and reducing the likelihood that flows will displace the material and expose a weak spot in the subgrade. ▪ Provides a growing medium that supports riparian vegetation.	▪ Requires mixing of only two different materials and, therefore requires less effort to order, stockpile, and mix materials. ▪ Requires less expertise and oversight during mixing and placing. ▪ Organic material within the growing medium supports riparian vegetation.
Disadvantages	▪ Requires mixing up to five or six different aggregates in the proper proportions. This requires additional effort in ordering, stockpiling, mixing, and placing materials compared to soil riprap. ▪ Difficult to inspect after installation because small void-material can cover larger riprap. Need to inspect <u>during</u> placement. ▪ Requires construction observation for submittal and sample material review, adjustments to the mix proportions to compensate for varying material gradation, approval of test fields mixing operations, and observation of placement and compaction. ▪ Costs more than soil riprap. ▪ If not well mixed, pockets of small void material, especially near surface can wash out and unravel void-filled riprap installation. Need to continually monitor and make sure larger riprap is not displaced and located at surface to provide sufficient D_{50}.	▪ Does not provide the same level of stability and armoring in areas of direct, continuous flow impingement.

8.1 Riprap Sizing

Procedures for sizing rock to be used in soil riprap, void-filled riprap, and riprap over bedding are the same.

8.1.1 Mild Slope Conditions

When subcritical flow conditions occur and/or slopes are mild (less than 2 percent), UDFCD recommends the following equation (Hughes, et al, 1983):

$$d_{50} \geq \left[\frac{VS^{0.17}}{4.5(G_s - 1)^{0.66}} \right]^2 \qquad \text{Equation 8-11}$$

Where:

V = mean channel velocity (ft/sec)

S = longitudinal channel slope (ft/ft)

d_{50} = mean rock size (ft)

Gs = specific gravity of stone (minimum = 2.50, typically 2.5 to 2.7), Note: In this equation (Gs -1) considers the buoyancy of the water, in that the specific gravity of water is subtracted from the specific gravity of the rock.

Note that Equation 8-11 is applicable for sizing riprap for channel lining with a longitudinal slope of no more than 2%. This equation is not intended for use in sizing riprap for steep slopes (typically in excess of 2 percent), rundowns, or protection downstream of culverts. Information on rundowns is provided in Section 7.0 of the *Hydraulic Structures* chapter of the USDCM, and protection downstream of culverts is discussed in the *Culverts and Bridges* chapter. For channel slopes greater than 2% use one of the methods presented in 8.1.2.

Rock size does not need to be increased for steeper channel side slopes, provided the side slopes are no steeper than 2.5H:1V (UDFCD 1982). Channel side slopes steeper than 2.5H:1V are not recommended because of stability, safety, and maintenance considerations. See Figure 8-34 for riprap placement specifications. At the upstream and downstream termination of a riprap lining, the thickness should be increased 50% for at least 3 feet to prevent undercutting.

8.1.2 Steep Slope Conditions

Steep slope rock sizing equations are used for applications where the slope is greater than 2 percent and/or flows are in the supercritical flow regime. The following rock sizing equations may be referred to for riprap design analysis on steep slopes:

- CSU Equation, *Development of Riprap Design Criteria by Riprap Testing in Flumes: Phase II* (prepared by S.R. Abt, et al, Colorado State University, 1988). This method was developed for steep slopes from 2 to 20 percent.

- USDA- Agricultural Research Service Equations, *Design of Rock Chutes* (by K.M. Robinson, et al, USDA- ARS, 1998 Transactions of ASAE) and *An Excel Program to Design Rock Chutes for Grade*

Stabilization, (K.M. Robinson, et al, USDA- ARS, 2000 ASAE Meeting Presentation). This method is based on laboratory data for slopes from 2 to 40 percent.

- USACE Steep Slope Riprap Equation, *Hydraulic Design of Flood Control Channels, EM1110-2-1601*, (June 1994). This method is applicable for slopes from 2 to 20 percent.

All three of the steep slope methods are based on two key parameters: unit discharge and slope. Flow concentration is one of the main problems that can develop along steep riprap slopes; both CSU and USACE methods recommend that the design unit discharge be increased by a flow concentration factor. When using the CSU equation or the USDA method, increase the largest rock size by approximately 30% when specifying standard UDFCD riprap gradations. This increase accounts for the fact that the steep slope equations were developed using poorly graded rock (uniform in size) unlike the well-graded gradations in UDFCD specifications. Additionally, for the reasons described in the following section, it is typical to also apply a safety factor of 1.5 or more times the calculated D50 riprap size when using any of these steep slope riprap sizing methods. When using the CSU equation or the USDA method apply the safety factor after increasing the largest rock size by 30%.

8.1.3 Design Safety Factor

Whether in mild slope or steep slope conditions, consider a safety factor when specifying the sides of riprap. Sizing methods presented in this manual were developed from controlled laboratory conditions. Field installation of rock is much less precise compared to laboratory conditions. It is difficult to grade riprap flat across a channel bottom or in a manner that provides a uniform slope. Sometimes the riprap delivered from local quarries is slightly smaller than specified. Flow conditions in streams can be affected by a variety of elements including debris, sedimentation, vegetation, etc. and can result in flow concentrations. It is important to include a safety factor when using these equations because the variability associated with conditions in the field cannot be quantified.

8.2 Boulder and Riprap Specifications

Specific material and installation specifications for riprap and boulders can be found in UDFCD's Construction Specifications, available at www.udfcd.org.

8.2.1 Boulders

Boulders may be placed and grouted or placed without grout. When not grouted, boulders require careful design to provide a firm foundation and stable configuration as well as properly graded backfill material sized to prevent migration of fine subgrade material through voids in the boulders. All stacked boulders require consideration of stability and any stacked boulder configuration over six feet in height requires a structural analysis to confirm proper design. Additionally, some municipalities require structural analysis and a building permit for walls greater than four feet.

Grouted boulders should follow the general guidelines described as part of the sections on grouted boulder grade control structures in the *Hydraulic Structures* Chapter and in the UDFCD Construction Specifications. See Figure 8-36 for typical construction of a grouted boulder bank protection.

8.2.2 Soil Riprap

Soil riprap is intended for use in applications where vegetative cover can be established in the riprap. When installed outside of the low-flow channel, UDFCD frequently specifies 4 to 6 inches of topsoil on top of soil riprap to help establish vegetation. Soil used in the voids and placed on top of the soil riprap should meet the description for viable topsoil composition for Colorado native plant establishment and upland areas as defined in the *Revegetation* chapter. See Figure 8-34 for gradation and placement of both riprap and soil riprap. Also see Figure 13 –19 in the *Revegetation* chapter for a fabric staking detail that can be used where fabric is specified over soil riprap. The combination of straw and coir mat is frequently used to help retain soil and seed. This is especially useful when topsoil is placed on top of soil riprap and then seeded. Specifications for mixing and installing soil riprap are further addressed in the UDFCD Construction Specifications.

8.2.3 Void-Filled Riprap

Void-filled riprap contains a well-graded mix of cobbles, gravels, sands, and soil that fills all voids and acts as an internal filter.

In addition to specifying the D_{50} rock size, individual material components that will make up the mix needed to be specified. The gradation of each material component should be specified by identifying a variety of particle sizes (from large to small) and the range of allowable “passing” percentages for each particle size. See Figure 8-35 for typical mixes of various sized rock, however, the designer should specify any mix adjustments based on the requirements of a particular project.

Photograph 8-18. Void-filled riprap is designed to emulate natural riffles, consisting of a mix of rock, gravels and sands that is densely-packed and able to support riparian vegetation.

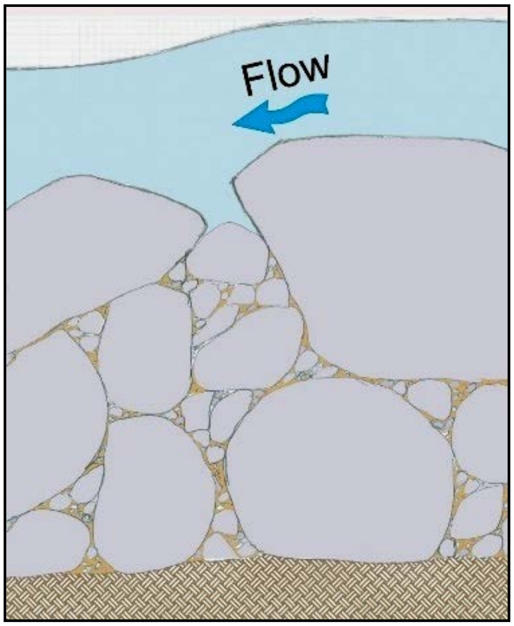


Figure 8-33. Small rock of void-filled riprap becomes “wedged in” under larger rock (Source: Muller Engineering Company)

Photograph 8-19. Seven-inch minus crushed surge is a key ingredient to fill gaps between riprap.

Photograph 8-20. Four-inch minus pit run surge is also an important ingredient to fill gaps between riprap.

Photograph 8-21. Void-filled riprap after placement and compaction.

Sufficient construction oversight by an engineer and/or a construction inspector knowledgeable in mixing and placing void-fill riprap is essential. This includes reviewing rock material submittals, field observation during initial mixing, and observation during placement of void-filled riprap. These construction services are summarized below; detailed specifications for mixing and placing void-filled riprap are provided in the UDFCD Construction Specifications available at www.udfcd.org.

1. **Material Submittals.** Laboratory test certificates, gradations, and suppliers for all materials included in the riffle rock mix should be submitted for review. If there is difficulty finding material that meets the specified gradation for a particular component, this can often be resolved by selecting a different supplier for that component.

2. **Mixing Void-Filled Riprap.** Individual void-filled riprap materials are typically delivered and unloaded onsite in separate stockpiles. Mixing is typically accomplished using a front end loader to add the proper “loader bucket” proportions of each material into one combined stockpile. Once all the materials have been added, the pile is mixed thoroughly to blend the materials together using the loader or large track hoe excavator. The goal is to fill the voids of the base riprap material **without displacing the riprap**. The interlocking nature of riprap in the mixed material needs to remain essentially the same as if the riprap was placed without void-fill material.

   The specified mix proportions are noted as approximate because the two surge materials vary somewhat between different suppliers and variations in gravel pits. Therefore, it is important that the design engineer is onsite during the first mixing operation to make slight adjustments to the proportions if necessary.

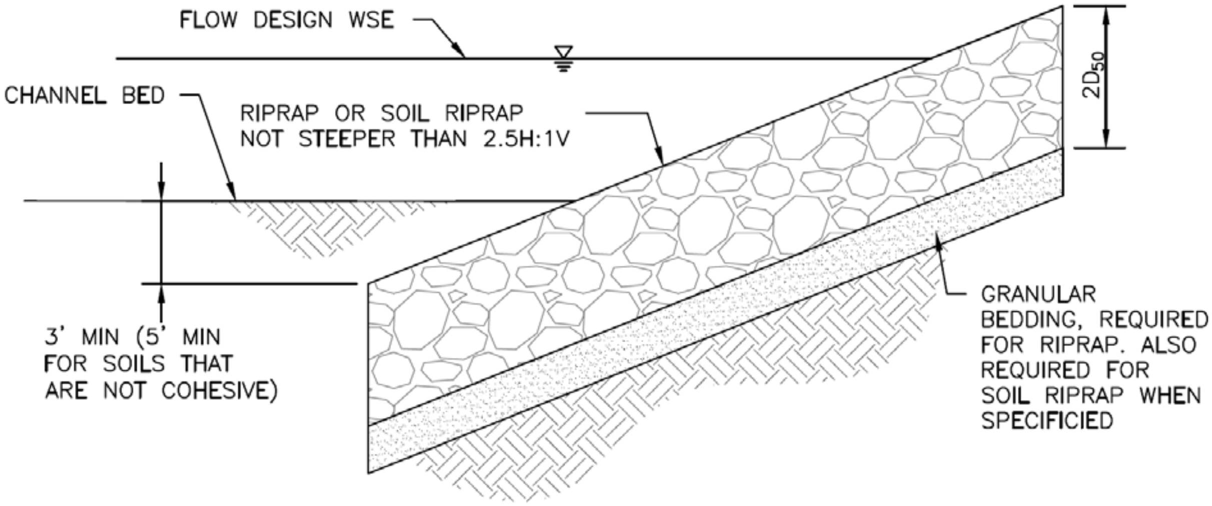
3. **Placing Void-Filled Riprap**. Void-filled riprap can be challenging to place as it has a tendency to segregate. Finer sands and gravels will separate from the larger riprap. Contractors must take care to minimize segregation when hauling the mixed material from the stockpile to the installation location.

   Loose material must be placed in a single lift of sufficient height such that final grade will be achieved upon compaction. In most cases, some additional mixing with a track excavator is needed after the initial placement to make sure that void-filled riprap is thoroughly mixed and that there is no segregation or areas where the void-filled riprap consists primarily of the smaller void-fill materials. A pocket of fine void-fill materials near the surface, without sufficient larger riprap, can get washed out and create flow concentrations that could unravel the void-filled riprap installation. **The goal is to fill the riprap voids without displacing riprap.**

   The last step is to compact the loosely placed void-filled riprap material by driving over it with a heavy duty loader or similar equipment. Water should be added, if necessary, so that the moisture content of the mixture is at optimum conditions during the compaction process.

   It is important that the finished top elevation of the void-filled riprap layer closely matches design grades to within a tolerance of 0.10 feet. Having a tight elevation tolerance helps to minimize development of flow concentrations. Finally, if for some reason the compacted material ends up below final grade, it is not acceptable to allow placement of only the smaller void-fill material or additional top dressing cobbles to achieve final grade. In such cases it is necessary to add more standard sized void-filled riprap and remix the entire thickness of rock to achieve the design section.

   To ensure proper mixing and placement of void-filled riprap, UDFCD recommends construction of a test section. Requiring the approval of a test section helps to ensure that the contractor understands construction requirements at the start of a project and can make adjustments as necessary during construction.



RIPRAP DESIGNATION	% SMALLER THAN GIVEN SIZE BY WEIGHT	INTERMEDIATE ROCK DIMENSION (INCHES)	D_{50}* (INCHES)
TYPE VL	70 – 100 50 – 70 35 – 50 2 – 10	12 9 6 2	6
TYPE L	70 – 100 50 – 70 35 – 50 2 – 10	15 12 9 3	9
TYPE M	70 – 100 50 – 70 35 – 50 2 – 10	21 18 12 4	12
TYPE H	70 – 100 50 – 70 35 – 50 2 – 10	30 24 18 6	18
*D_{50} = MEAN ROCK SIZE			

Figure 8-34. Riprap and soil riprap placement and gradation (part 1 of 3)

SOIL RIPRAP NOTES:

1. ELEVATION TOLERANCES FOR THE SOIL RIPRAP SHALL BE 0.10 FEET. THICKNESS OF SOIL RIPRAP SHALL BE NO LESS THAN THICKNESS SHOWN AND NO MORE THAN 2–INCHES GREATER THAN THE THICKNESS SHOWN.

2. WHERE “SOIL RIPRAP” IS DESIGNATED ON THE CONTRACT DRAWINGS, RIPRAP VOIDS ARE TO BE FILLED WITH NATIVE SOIL. THE RIPRAP SHALL BE PRE–MIXED WITH THE NATIVE SOIL AT THE FOLLOWING PROPORTIONS BY VOLUME: 65PERCENT RIPRAP AND 35 PERCENT SOIL. THE SOIL USED FOR MIXING SHALL BE NATIVE TOPSOIL AND SHALL HAVE A MINIMUM FINES CONTENT OF 15 PERCENT. THE SOIL RIPRAP SHALL BE INSTALLED IN A MANNER THAT RESULTS IN A DENSE, INTERLOCKED LAYER OF RIPRAP WITH RIPRAP VOIDS FILLED COMPLETELY WITH SOIL. SEGREGATION OF MATERIALS SHALL BE AVOIDED AND IN NO CASE SHALL THE COMBINED MATERIAL CONSIST PRIMARILY OF SOIL; THE DENSITY AND INTERLOCKING NATURE OF RIPRAP IN THE MIXED MATERIAL SHALL ESSENTIALLY BE THE SAME AS IF THE RIPRAP WAS PLACED WITHOUT SOIL.

3. WHERE SPECIFIED (TYPICALLY AS “BURIED SOIL RIPRAP”), A SURFACE LAYER OF TOPSOIL SHALL BE PLACED OVER THE SOIL RIPRAP ACCORDING TO THE THICKNESS SPECIFIED ON THE CONTRACT DRAWINGS. THE TOPSOIL SURFACE LAYER SHALL BE COMPACTED TO APPROXIMATELY 85% OF MAXIMUM DENSITY AND WITHIN TWO PERCENTAGE POINTS OF OPTIMUM MOISTURE IN ACCORDANCE WITH ASTM D698. TOPSOIL SHALL BE ADDED TO ANY AREAS THAT SETTLE.

4. ALL SOIL RIPRAP THAT IS BURIED WITH TOPSOIL SHALL BE REVIEWED AND APPROVED BY THE ENGINEER PRIOR TO ANY TOPSOIL PLACEMENT.

GRADATION FOR GRANULAR BEDDING

U.S. STANDARD SIEVE SIZE	PERCENT PASSING BY WEIGHT	
	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

RIPRAP BEDDING

Figure 8-34. Riprap and soil riprap placement and gradation (part 2 of 3)

THICKNESS REQUIREMENTS FOR GRANULAR BEDDING			
RIPRAP DESIGNATION	MINIMUM BEDDING THICKNESS (INCHES)		
	FINE–GRAINED SOILS [1]		COARSE–GRAINED SOILS [2]
	TYPE I (LOWER LAYER)	TYPE II (UPPER LAYER)	TYPE II
VL (D_{50} = 6 IN)	4	4	6
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

NOTES:

1. 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.
2. FIFTY PERCENT OR MORE BY WEIGHT RETAINED ON THE #40 SIEVE.

Figure 8-34. Riprap and soil riprap placement and gradation (part 3 of 3)

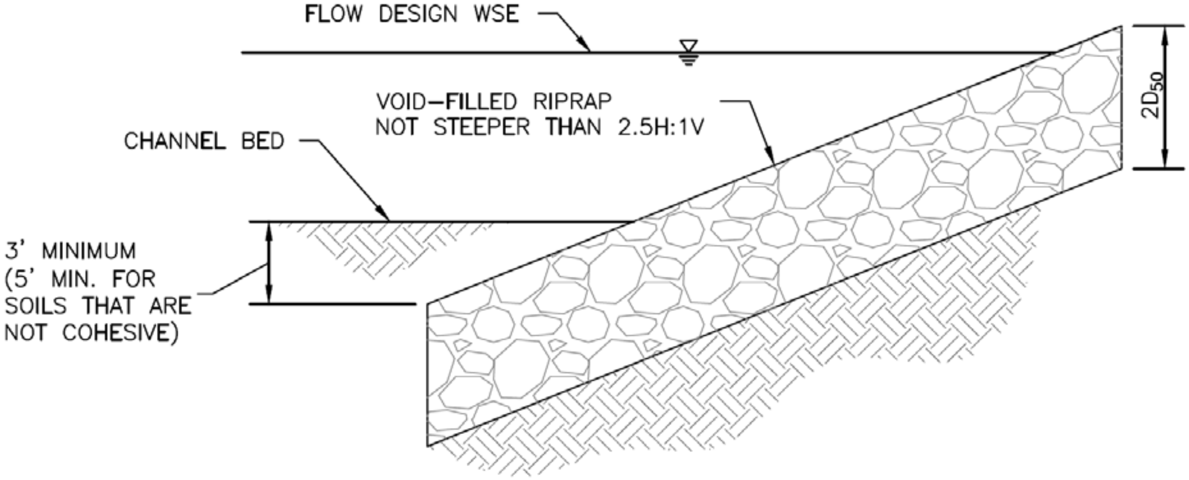


TABLE 1. MIX REQUIREMENTS FOR TYPE VL AND L VOID–FILLED RIPRAP (D_{50} = 6 TO 9 INCH)

APPROPRIATE PROPORTIONS (BY VOLUME)	MATERIAL TYPE	MATERIAL DESCRIPTION
6 PARTS	RIPRAP	D_{50} = 6 INCH (TYPE VL) OR D_{50} = 9 INCH (TYPE L), SEE TABLE 3
1 PART	VOID–FILL MATERIAL	VTC (VEHICLE TRACKING CONTROL) ROCK (CRUSHED ROCK WITH 100% PASSING 4–INCH SIEVE, 50–70% PASSING 3–INCH SIEVE, 0–10% PASSING 2–INCH SIEVE)
1 PART	VOID–FILL MATERIAL	4–INCH MINUS PIT RUN SURGE (ROUND RIVER ROCK AND SAND, WELL GRADED, 90–100% PASSING 4–INCH SIEVE, 70–80% PASSING 1½–INCH SIEVE, 40–60% PASSING ⅜–INCH SIEVE, 10–30% PASSING #16 SIEVE)
1 PART	VOID–FILL MATERIAL	TYPE II BEDDING (CRUSHED ROCK WITH 100% PASSING 3–INCH SIEVE, 20–90% PASSING ¾–INCH SIEVE, 0–20% PASSING #4 SIEVE, 0–3% PASSING #200 SIEVE)
½ TO 1 PART	VOID–FILL MATERIAL	NATIVE TOPSOIL

VOID–FILLED RIPRAP PLACEMENT AND GRADATION

Figure 8-35. Void-filled riprap placement and gradation (part 1 of 3)

TABLE 2. MIX REQUIREMENTS FOR TYPE M AND H VOID–FILLED RIPRAP (D_{50} = 12 TO 18 INCH)

APPROPRIATE PROPORTIONS (BY VOLUME)	MATERIAL TYPE	MATERIAL DESCRIPTION
6 PARTS	RIPRAP	D_{50} = 12–INCH (TYPE M) OR D_{50} = 18–INCH (TYPE H), SEE TABLE 3
2 PART	VOID–FILL MATERIAL	7–INCH MINUS CRUSHED ROCK SURGE (100% PASSING 7–INCH SIEVE, 80–100% PASSING 6–INCH SIEVE, 35–50% PASSING 3–INCH SIEVE, 10–20% PASSING 1½–INCH SIEVE)
1 PART	VOID–FILL MATERIAL	VTC (VEHICLE TRACKING CONTROL) ROCK (CRUSHED ROCK WITH 100% PASSING 4–INCH SIEVE, 50–70% PASSING 3–INCH SIEVE, 0–10% PASSING 2–INCH SIEVE)
1 PART	VOID–FILL MATERIAL	4–INCH MINUS PIT RUN SURGE (ROUND RIVER ROCK AND SAND, WELL GRADED, 90–100% PASSING 4–INCH SIEVE, 70–80% PASSING 1½–INCH SIEVE, 40–60% PASSING ⅜–INCH SIEVE, 10–30% PASSING #16 SIEVE)
1 PART	VOID–FILL MATERIAL	TYPE II BEDDING (CRUSHED ROCK WITH 100% PASSING 3–INCH SIEVE, 20–90% PASSING ¾–INCH SIEVE, 0–20% PASSING #4 SIEVE, 0–3% PASSING #200 SIEVE)
½ TO 1 PART	VOID–FILL MATERIAL	NATIVE TOPSOIL

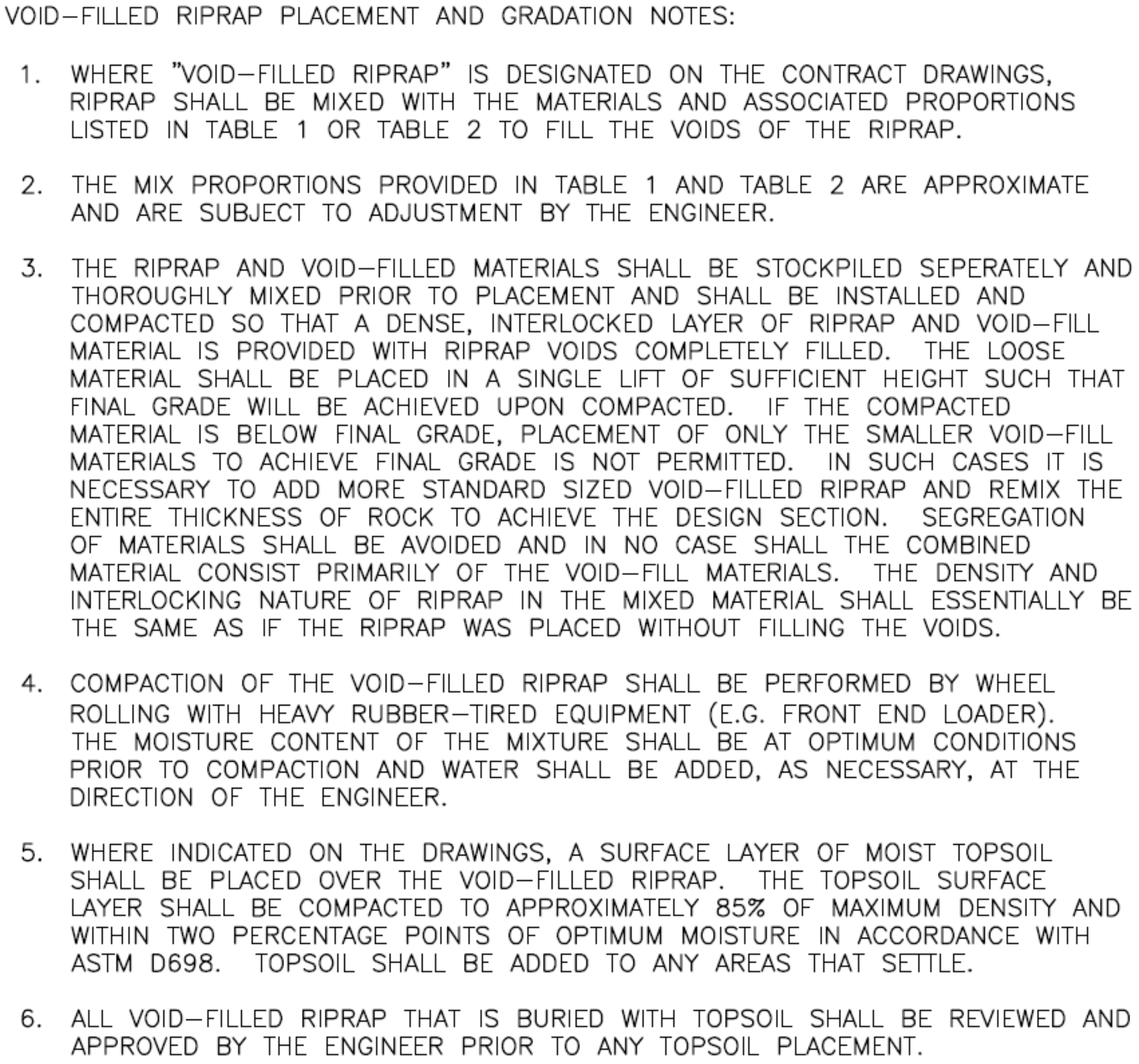
TABLE 3. VOID–FILLED RIPRAP PLACEMENT AND GRADATION

RIPRAP DESIGNATION	% SMALLER THAN GIVEN SIZE BY WEIGHT	INTERMEDIATE ROCK DIMENSION (INCHES)	D_{50}* (INCHES)
TYPE VL	70 – 100 50 – 70 35 – 50 2 – 10	12 9 6 2	6
TYPE L	70 – 100 50 – 70 35 – 50 2 – 10	15 12 9 3	9
TYPE M	70 – 100 50 – 70 35 – 50 2 – 10	21 18 12 4	12
TYPE H	70 – 100 50 – 70 35 – 50 2 – 10	30 24 18 6	18

*D_{50} = MEAN ROCK SIZE

NOTE: MIX ON SITE AND PRIOR TO PLACEMENT

Figure 8-35. Void-filled riprap placement and gradation (part 2 of 3)



VOID-FILLED RIPRAP PLACEMENT AND GRADATION NOTES:

1. WHERE ”VOID-FILLED RIPRAP” IS DESIGNATED ON THE CONTRACT DRAWINGS, RIPRAP SHALL BE MIXED WITH THE MATERIALS AND ASSOCIATED PROPORTIONS LISTED IN TABLE 1 OR TABLE 2 TO FILL THE VOIDS OF THE RIPRAP.

2. THE MIX PROPORTIONS PROVIDED IN TABLE 1 AND TABLE 2 ARE APPROXIMATE AND ARE SUBJECT TO ADJUSTMENT BY THE ENGINEER.

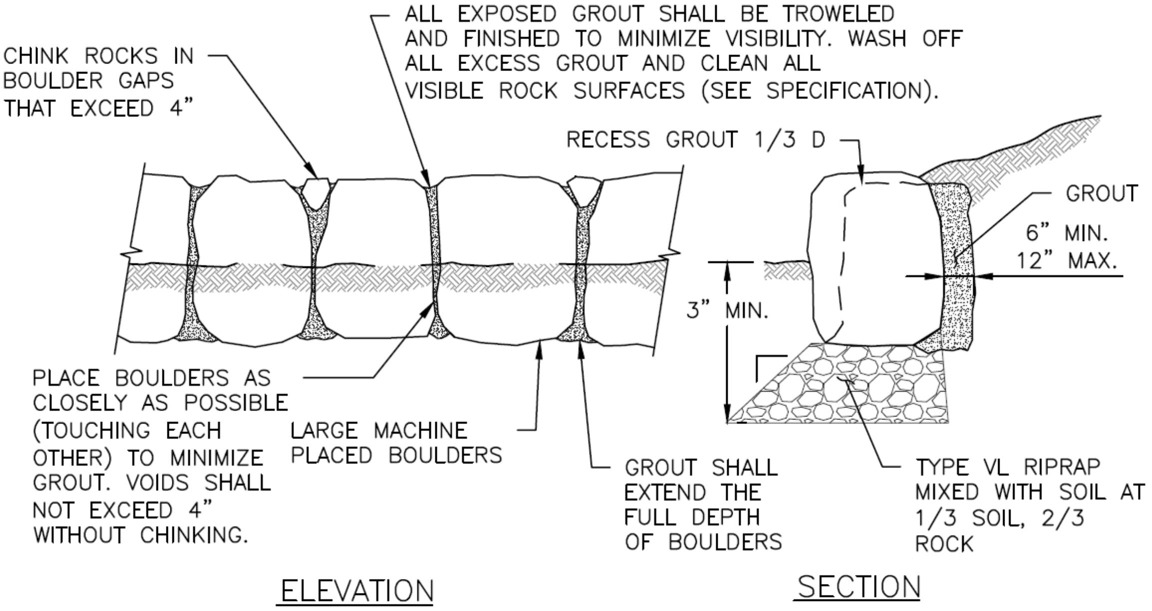
3. THE RIPRAP AND VOID-FILLED MATERIALS SHALL BE STOCKPILED SEPERATELY AND THOROUGHLY MIXED PRIOR TO PLACEMENT AND SHALL BE INSTALLED AND COMPACTED SO THAT A DENSE, INTERLOCKED LAYER OF RIPRAP AND VOID-FILL MATERIAL IS PROVIDED WITH RIPRAP VOIDS COMPLETELY FILLED. THE LOOSE MATERIAL SHALL BE PLACED IN A SINGLE LIFT OF SUFFICIENT HEIGHT SUCH THAT FINAL GRADE WILL BE ACHIEVED UPON COMPACTED. IF THE COMPACTED MATERIAL IS BELOW FINAL GRADE, PLACEMENT OF ONLY THE SMALLER VOID-FILL MATERIALS TO ACHIEVE FINAL GRADE IS NOT PERMITTED. IN SUCH CASES IT IS NECESSARY TO ADD MORE STANDARD SIZED VOID-FILLED RIPRAP AND REMIX THE ENTIRE THICKNESS OF ROCK TO ACHIEVE THE DESIGN SECTION. SEGREGATION OF MATERIALS SHALL BE AVOIDED AND IN NO CASE SHALL THE COMBINED MATERIAL CONSIST PRIMARILY OF THE VOID-FILL MATERIALS. THE DENSITY AND INTERLOCKING NATURE OF RIPRAP IN THE MIXED MATERIAL SHALL ESSENTIALLY BE THE SAME AS IF THE RIPRAP WAS PLACED WITHOUT FILLING THE VOIDS.

4. COMPACTION OF THE VOID-FILLED RIPRAP SHALL BE PERFORMED BY WHEEL ROLLING WITH HEAVY RUBBER-TIRED EQUIPMENT (E.G. FRONT END LOADER). THE MOISTURE CONTENT OF THE MIXTURE SHALL BE AT OPTIMUM CONDITIONS PRIOR TO COMPACTION AND WATER SHALL BE ADDED, AS NECESSARY, AT THE DIRECTION OF THE ENGINEER.

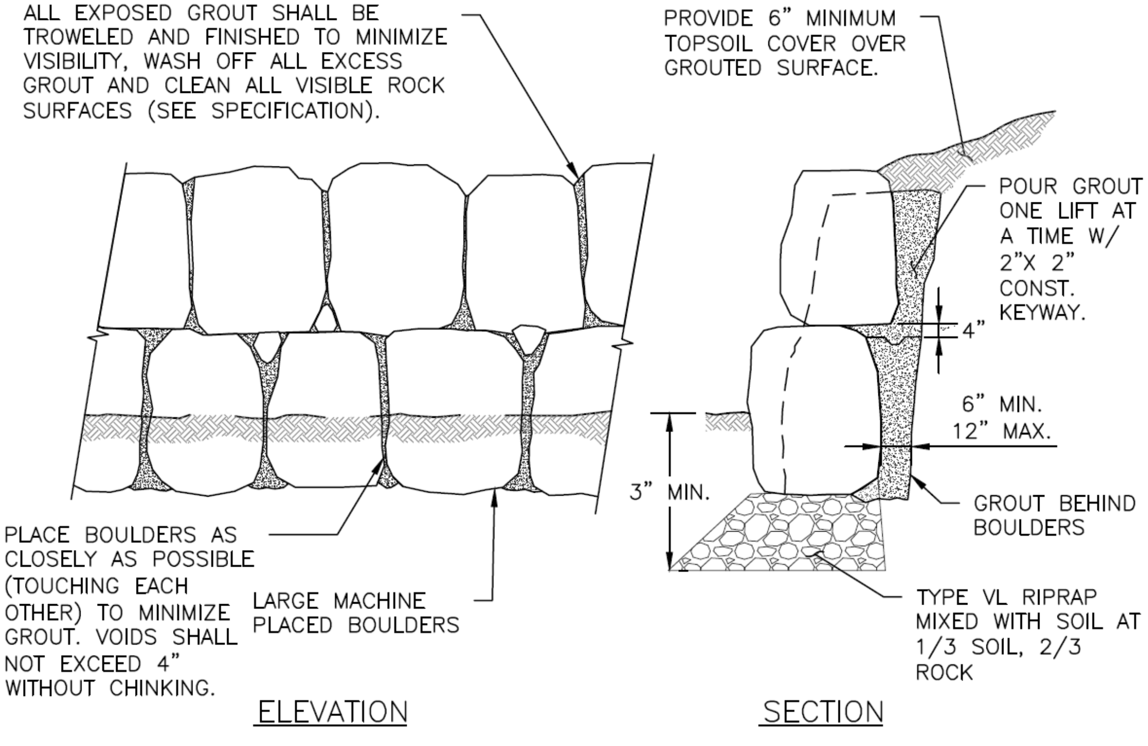
5. WHERE INDICATED ON THE DRAWINGS, A SURFACE LAYER OF MOIST TOPSOIL SHALL BE PLACED OVER THE VOID-FILLED RIPRAP. THE TOPSOIL SURFACE LAYER SHALL BE COMPACTED TO APPROXIMATELY 85% OF MAXIMUM DENSITY AND WITHIN TWO PERCENTAGE POINTS OF OPTIMUM MOISTURE IN ACCORDANCE WITH ASTM D698. TOPSOIL SHALL BE ADDED TO ANY AREAS THAT SETTLE.

6. ALL VOID-FILLED RIPRAP THAT IS BURIED WITH TOPSOIL SHALL BE REVIEWED AND APPROVED BY THE ENGINEER PRIOR TO ANY TOPSOIL PLACEMENT.

Figure 8-35. Void-filled riprap placement and gradation (part 3 of 3)



GROUTED BOULDER EDGE DETAIL



GROUTED BOULDER STACKED WALL EDGE

Figure 8-36. Sample grouted boulder section

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