Chapter 12
Open Channels

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1.0 Introduction

This chapter summarizes the analysis and design methodology for projects that impact drainageways and describes methods for preserving natural drainageway features. Applicable criteria and design considerations are provided for stabilization of common channel types. Additional guidance required to complete channel design projects is provided in the Major Drainage and Hydraulic Structures Chapters of the UDFCD Manual.

1.1 Natural Drainageways

Natural drainageways are those that have developed from natural causes, as opposed to being human-made or having developed entirely as a result of urban runoff. A drainageway does not have to be entirely untouched by humans to function as a natural channel. Many natural drainageways in or near developed areas have been altered to some extent by human activity and exhibit varying degrees of impacts and stability. As shown in Figure 12-1, natural drainageways provide a number of important environmental and ecological functions and benefits, including:

1. Stable conveyance of baseflow and storm runoff.
2. Support of wetland and riparian vegetation.
3. Creation of habitat for wildlife and aquatic species.
4. Slowing and attenuating floodwater by spreading flows over vegetated overbanks.
5. Promotion of infiltration and groundwater recharge.
6. Enhancement of water quality.
7. Provision of corridors for trails and open space.
8. Enhancement of property values and quality of life.

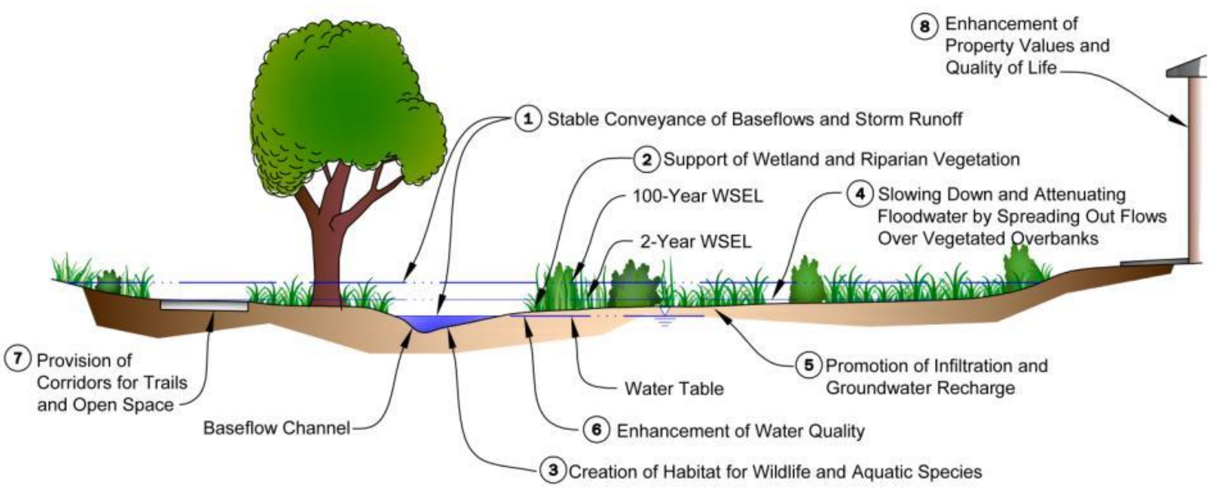


Figure 12-1. Functions and Benefits of Natural Drainageways

Natural drainageways are dynamic, responding to changes in flow, vegetation, geometry, and sediment supply that are imposed in developing urban environments. As a result, natural streams often face threats that can degrade their functions and benefits. Goals for the design of channels in an urbanizing environment include preserving the beneficial functions of natural channels, enhancing channels to improve functions, where practical, and mitigating the impacts of development. The designer's ability to accomplish these goals is affected by current and long-term conditions in the drainage basin upstream of the project reach.

1.2 Impacts of Urbanization

Urbanization typically increases the frequency, duration, volume, and peak flow of stormwater runoff and may also include filling and developing portions of the floodplain. Urbanization can introduce water sources unrelated to storm events (e.g., irrigation and treated sanitary wastewater discharges) that affect channel conditions. Additionally, the natural supply of watershed sediment is often reduced relative to undeveloped conditions when natural cover is replaced with paved areas and detention and stormwater quality ponds are installed. All of these factors contribute to the tendency of urban drainageways to degrade and incise as streams seek a new condition of equilibrium, producing negative impacts to instream habitats, riparian environments and adjacent properties, as illustrated in Figure 12-2 and described below.

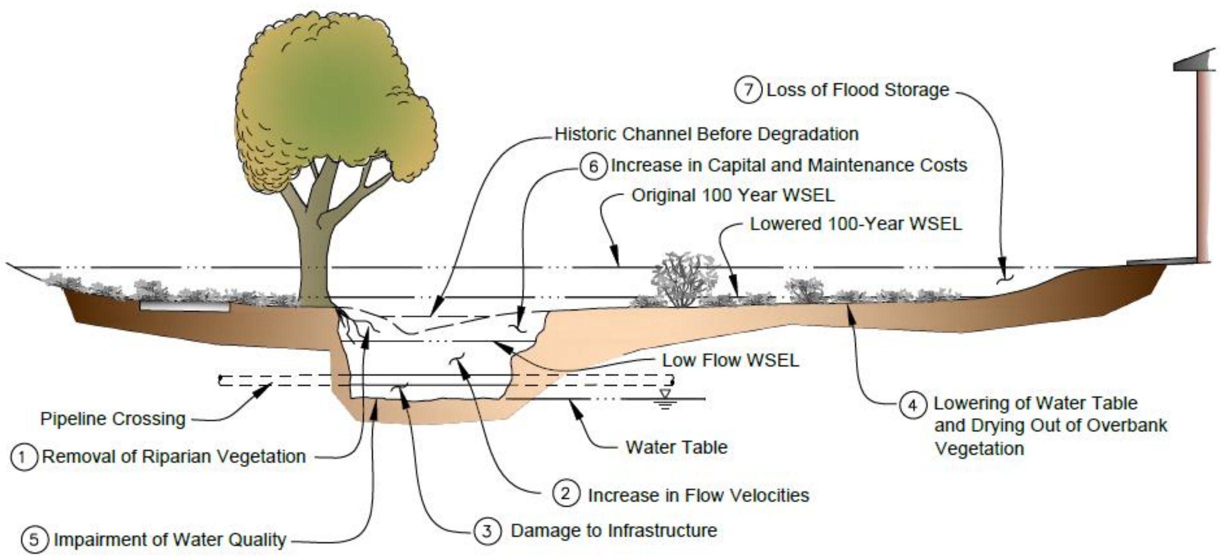


Figure 12-2. Impacts of Stream Degradation

1. **Removal of Riparian Vegetation.** Erosion typically strips natural vegetation from the bed and banks of drainageways. This disrupts habitat for aquatic and terrestrial species and leaves the channel exposed to further erosion damage. Subsequent bank erosion and undercutting increases the risk of excessive sediment and nutrient loading to downstream waterbodies.

2. **Increase in Velocity and Shear.** An incised channel concentrates runoff and increases flow velocities and shear stresses on the channel perimeter. It is not unusual for channel velocities to increase significantly in an incised condition. Stream flow conditions with erosive potential also occur more frequently. Additionally, a "feedback loop" may develop where incision leads to increased erosive capacity and then further incision. Once started, this process typically

continues until a new channel invert is established, potentially resulting in bare, near-vertical channel banks in place of the well vegetated, gently sloping banks of natural channels and a main channel disconnected from the natural floodplain. Knick points or "headcuts" generated by increases in velocity and shear can rapidly spread erosion impacts throughout drainage networks in the absence of effective grade controls.

3. **Damage to Infrastructure.** Channel erosion can threaten utility lines, bridges, and other infrastructure. Utility pipelines that were originally constructed several feet below the bed of a creek may become exposed as the channel bed lowers. 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 expose buried utility lines, undermine roadways and cause significant damage to adjacent properties and structures.

4. **Lowering of Water Table and Drying-out of Overbank Vegetation.** In many cases, lowering of the channel thalweg and baseflow elevation leads to a corresponding lowering of the local water table. Lowering the water table can have a negative effect on bank stability and aquatic and terrestrial ecology. Substantial lowering of the channel invert can make water inaccessible to wetland and mesic plant species, causing them to die out and be replaced by upland species which have poorer ground coverage, canopy and root structure. The result can be degradation or elimination of both aquatic and terrestrial habitat and destabilization of the channel banks.

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 1-foot deep across a width of 10 feet produces almost 2,000 cubic yards of sediment that could be deposited in downstream lakes and stream reaches. Along the Front Range of Colorado, these sediments contain phosphorus, a nutrient that can lead to accelerated eutrophication of lakes and reservoirs. Along some reaches of Fountain Creek, naturally occurring selenium can be mobilized into the stream system by urbanization and erosion into underlying geologic formations. Also, channel incision impairs the "cleansing" function that natural floodplain overbanks can provide through settling, vegetative filtering, wetland treatment processes, and infiltration.

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

7. **Loss of Flood Storage.** Incision of the low-flow or main channel portion of the drainageway prevents flood flows from spilling into the overbank area where the natural storage helped to reduce downstream peak flows.

1.3 Vision for Drainageways

The vision for drainageways as described in this Manual is to go beyond simply stabilizing a channel against erosion and to implement enhanced stream stabilization. Stabilization can be accomplished by lining a channel with concrete; however, not only is this often the most expensive approach to stabilization, it also eliminates the ecological, aesthetic and recreational value of drainageways. Enhanced stream stabilization has the goal of maintaining or restoring natural streams and well-vegetated floodplains that are physically and biologically healthy, with the attributes shown in Figure 12-1. Plan form and cross-sectional geometry, riparian vegetation, grade-control features, and flood storage provisions should be integrated into channel designs to emulate the functions of natural features to the extent practical. This vision is based on recognition that streams and drainageways are a valuable resource to the community and that capital and long-term maintenance costs to the community are typically lower when channel designs work with nature rather than against it. The implementation of these concepts is directly related to upstream basin conditions, including land uses, anticipated flows and flow control measures.

1.4 Design Flows

Flows conveyed by open channel are highly variable; therefore, it is not feasible to evaluate all of the possible flows a channel might convey. To simplify open channel design procedures, representative design flows have been identified. In most cases, open channel projects can be adequately designed using estimates of baseflows, low flows and flood flows. Full descriptions of these design flows and methods for estimating them are described in Chapter 6, Hydrology. General descriptions of these flow conditions include:

- Baseflows may not be directly related to storm events and are often not present in undeveloped drainage basins, but can become present after development. Their presence or absence can be a determining factor in the feasibility of implementing certain channel features, such as wetland bottoms.

- Low flows are normally contained within a well-defined channel that only overtops when a significant storm event occurs. Flows within this range are usually responsible for establishing the main channel section and the slope of the stream bed. The range of flows between baseflows and bank full capacity are generally those that are responsible for most of the geomorphic (channel shaping) activity and sediment transport. When a “natural” channel is planned or a natural channel is being preserved, special attention should be paid to this range of flows.

- Flood flows include any flows that exceed the low-flow or main channel capacity and have the potential to create unsafe or damaging conditions.

Open channel designs must account for each of these types of design flows and upstream drainage basin conditions, including practices implemented to reduce runoff volumes and other factors. By designing for these design flows, it is expected that adequate protection and conveyance will be provided for intermediate flows and that the proposed vision for drainageways can be achieved.

1.5 Sediment Load

The range of sediment loads carried by channels is affected by conditions and flows in the upstream drainage basin, impacts to the channel due to crossings or modifications, development activity and the extent of development-related improvements. Temporary sediment loads may differ from longer-term sediment loads. It is normally desirable to pass sediment through a design reach by designing the low-flow channel with sufficient hydraulic capacity to ensure that excessive sediment is not deposited in the reach over time. When evaluating a “design reach” the engineer should consider upstream and downstream potential for channel erosion and deposition, as hydraulic characteristics of the upstream and downstream reaches will affect the “design reach.” Estimates of the sediment load entering the project reach can be made by an analysis of the capacity and type of material conveyed in the upstream reaches. However, applying these methods can require extensive data collection and expertise that is often not available. Any project that requires these types of analyses must include a thorough description of the data sources and methodology to be used and submitted for approval. The City Engineer will determine if sediment load, deposition and/or scour analysis is required for a given project.

1.6 Channel Types

Open channels are influenced by changes in the upstream drainage basin contributing to the project reach as described above or by crossing structures, encroachments, debris and/or changes to vegetation within the project reach. The implementation of detention practices to attenuate peak flow rates and reduce cumulative erosion potential from urbanized areas is an important factor for assessing the feasibility of various channel types in terms of channel capacity and stability. The design of open channels must account for the effects of these factors over the design life of the project. Typical characteristics of the most common open channel types are described below, and in Table 12-1

Table 12-1. Channel Types

Channel Type	Typical Drainage Area[1]	Design Flows[2]	Sediment Loads[3]	Floodplain Preservation /ROW	Vegetation	Stabilization
Modified Natural Channel	>approx. 130 acres	Qf ≃ Qh	Sf ≤ Sh	Preservation of most of the floodplain and natural channel functions/ available ROW.	Limited disturbance/ native or compatible plant species and wetlands.	Generally limited to areas of instability and low-flow grade control, soil riprap, boulders, sculpted concrete, bioengineering, other compatible materials.
Constructed Natural Channel	<approx. 640 acres	Qf > Qh	Sf < Sh	Limited to full floodplain preservation/ provide natural channel functions when feasible/ROW availability varies.	Limited to significant revegetation, some preservation of natural vegetation, revegetation using native or compatible plant species and wetlands.	Low-flow stabilization and grade controls and possible full-channel-width grade controls.
Constructed Channel	<approx. 130 acres	Qf >> Qh	Sf << Sh	Almost no floodplain preservation/ limited to no natural channel function.	Limited revegetation/ normally hard-lined.	Fully stabilized with linings (riprap, soil riprap, concrete, grouted boulders, etc.) and full-width drop structures.

[1]Typical drainage areas may vary depending on approved master plans.
[2]Qh=historic flows, Qf=future flows
[3]Sh=historic sediment loads, Sf=future sediment loads

1.6.1 Major Drainageways

In general, major drainageways are streams with contributing drainage basin areas greater than approximately 130 acres. This threshold generally corresponds to the threshold for regional detention facilities as described in the Storage Chapter of this Manual. As a watershed urbanizes, providing detention storage (and volume reduction practices) upstream of or in the headwaters of major drainageways is advisable to minimize changes to hydrology that have the potential to affect stream stability and capacity needed in the drainageway. The amount of sediment transport in these drainageways can vary greatly depending on their location relative to upstream detention storage and the level of development; therefore, sediment transport estimates and stable slope considerations can also be important factors for designing major drainageways.

Projects affecting major drainageways must be completed so that natural drainageway features and benefits are preserved (and enhanced when feasible) or restored, unless otherwise designated in an approved master plan. Planning documents shall accurately identify all existing drainageways, floodplains, and other site features that may have beneficial natural features. Features proposed to be left in place and preserved or restored shall be clearly shown on the planning and/or design documents. A key consideration in the preservation of natural drainageways is obtaining an adequate easement of land that allows the drainageway to provide the natural function of flood storage and to allow the creation of open spaces that can provide habitat. This approach to channel design can also reduce the need to modify floodplain maps used in the administration of the National Flood Insurance Program (NFIP).

To the extent practical, major drainageway projects should protect and preserve these features, if present:

- General protection of aquatic and riparian habitat for threatened and non-threatened species that comprise a health ecosystem.
- Jurisdictional wetlands.
- Riparian vegetation such as cottonwood or willow trees, shrub willows, and wetland or transitional grasses.
- Baseflows.
- Overbank flood storage.
- Bedrock outcroppings or unique landforms.
- Historic, cultural, or archeological resources.

To complete the design of an open channel project, baseflows, low flows, and flood flows should be evaluated. At the discretion of the City Engineer, sediment transport evaluation may also be required. The evaluation of flood flows will normally include delineation of the floodplain for land planning purposes and for maintaining adequate freeboard at structures on adjacent developments and may also include scour calculations for utility crossings, bridge abutments and other structures. When the floodplain for the project reach is defined on a Flood Insurance Rate Map (FIRM), a revision to the regulatory floodplain may be necessary according to Chapter 5, Floodplain Management.

1.6.1.1 Modified Natural Channels

Most major drainageway projects can be described as modified natural channels. These projects require limited modifications to drainageways that allow most of the benefits of natural channels to be preserved or enhanced. Improvements will normally be limited to stabilization of the low-flow channel (unless a meandering low-flow channel is planned), crossing structures, grade control structures and limited stabilization of the banks to manage unstable areas or protect infrastructure. Loss of flood storage due to encroachments should be mitigated by providing compensatory storage. Considerations for modified natural channels include:

1. **Preserving Streams Not Yet Significantly Impacted.** Drainageways that have not yet experienced degradation from increased urban runoff or other forms of erosion should be preserved by implementing the following improvements:

   - Grade control structures to limit degradation in the low-flow channel, stabilize existing headcutting and establish a flatter equilibrium slope than may have existed previously.

   - Utilization of vegetated overbank benches adjacent to the low-flow channel to allow flood flows to spread out and slow down and to dissipate energy.

   - Stabilized low-flow channel that can be vegetated, potentially with a bioengineered or wetland bottom.

   - Bank stabilization at select locations where existing instability or the potential for future instability is identified.

   - Planting supplemental vegetation to provide for the transition to species suited for "wetter" urban hydrology. Additional moisture can sustain wetland and riparian vegetation. These grasses, sedges and rushes, shrubs, and trees can help to stabilize the channel and provide diverse habitat for wildlife.

2. **Restoring Impacted Streams.** Drainageways that have already experienced significant erosion and down-cutting are to be addressed similarly to streams that are not yet degraded. However, eroded, incised channels should not be stabilized in a manner that retains the incised geometry with steep side banks. Instead, incised channels should be restored by raising the channel invert up to or near its historic elevation, allowing flood flows to spread out onto the natural floodplain, avoiding deep, concentrated flood flows within the main channel. The more a drainageway is allowed to degrade, the greater the disturbance will be required to provide restoration and the higher the cost will be. This is especially true if the channel is allowed to incise to a depth that exceeds the critical bank height for geotechnical stability and crosses the threshold for widening through slab failures of the banks.

   Fountain Creek has experienced significant erosion, downcutting and widening through a long reach in Woodland Park stretching from below Sheridan Avenue to just upstream of Safeway/Aspen Garden Way. Much of this segment has progressed to the third stage of the incised channel evolution model (CEM; Stage III Figure 12-3). In this stage, bank heights and angles have exceeded the threshold of geotechnical stability. Slab failures and widening have commenced and channel rehabilitation becomes more challenging compared to the second stage in which bank heights have not exceeded critical levels. In streams with high energy relative to bank material size and little storage of failed material at bank the toe, the width-depth ratio of channel may continue to increase to a point where a return quasi-equilibrium conditions becomes unlikely (CEM Stage V; Figure 12-3). This appears to be the case with this segment of the Fountain Creek main stem.

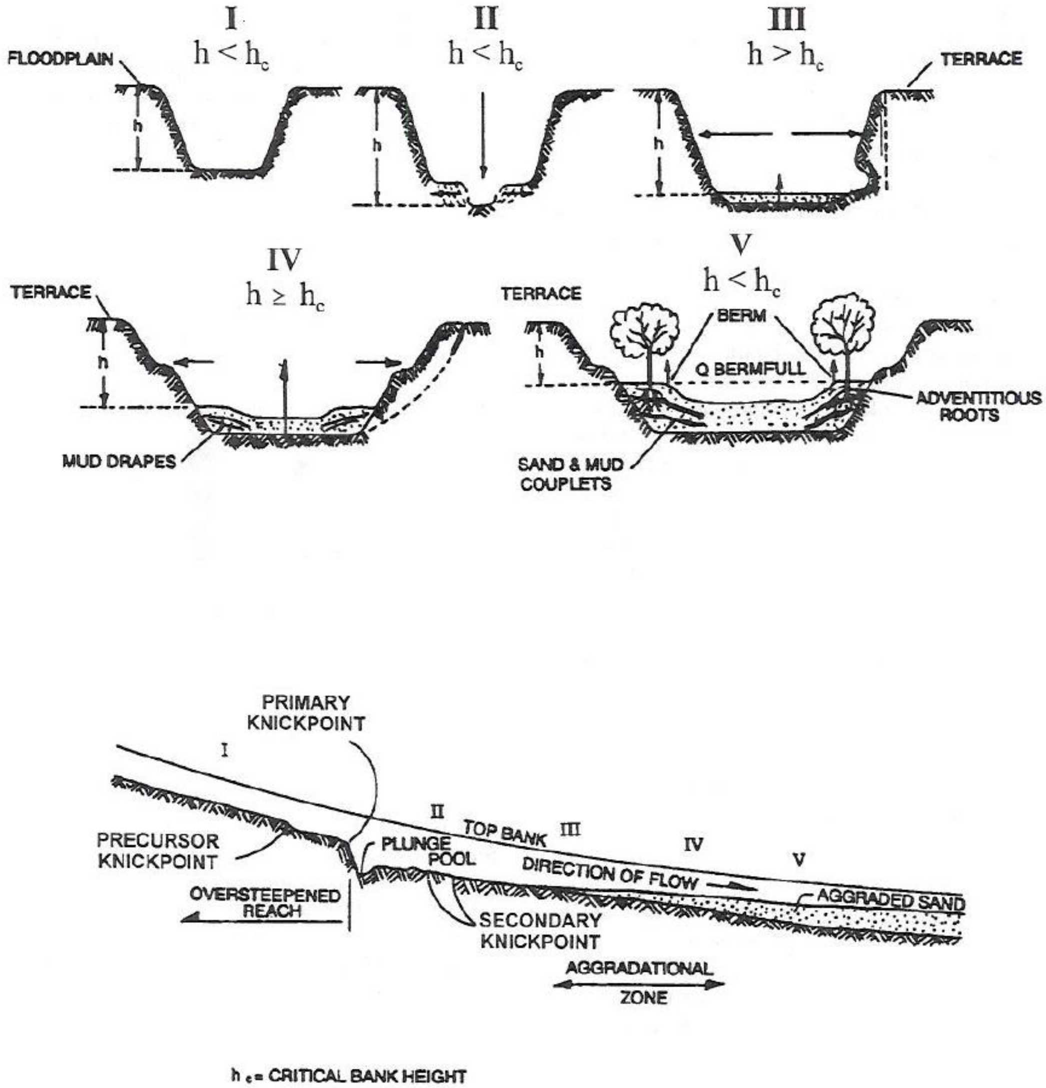


Figure 12-3. Incised Channel Evolution Model
(Schumm et al. 1984, Watson et al. 2002).

The City has developed plans to address these Stage III channel incision issues by constructing a long reinforced concrete box culvert. This is needed for this reach because of the extreme challenges and costs associated with re-creating a stable channel in an area with limited right-of-way, highly erodible soils, steep longitudinal channel slopes and significantly increased runoff (rate and volume) and decreased sediment supply from urbanized areas. While a box culvert is not an ideal solution to replace a reach of stream that once provided a number of the benefits depicted in Figure 12-1, the current condition of the stream exhibits most of the problems shown in Figure 12-2, and the box culvert will provided needed conveyance without the risk of infrastructure damage (exposed wastewater trunk line) and will dramatically reduce ongoing erosion along this reach.

The channel evolution model also indicates that the return to quasi-equilibrium conditions in downstream segments (e.g., aggradational reach behind Wal-Mart) is linked with the sediment supply provided by incising reaches upstream. As such, the management of incised channels is most effective when undertaken with a system level perspective that accounts for the potential for upstream stabilization to create sediment deficits in downstream reaches. This also underscores the importance ongoing monitoring to identify incising stream segments before channels cross the bank stability threshold between CEM Stages II and III. Watson et al. (2002) provide a discussion of how the CEM can guide the evaluation of incised channel rehabilitation alternatives.

3. **Channel Crossings.** When influences to a natural channel are limited to a structural crossing such as a roadway and the upstream drainage basin is not expected to change significantly over time, the design process must fully consider historic basin conditions and the natural conditions of the drainageway. Construction of the crossing should seek to minimize the impacts to the natural functions of the drainageway and provide mitigation for unavoidable impacts. In this situation, the project should avoid encroachment into and the modification of the adjacent floodplain and interference with the natural tendencies of the drainageway such as meandering and sediment transport. This is best achieved by structures that span all or most of the floodplain (at least near crossings where there is typically contraction and expansion of the flow). When floodplain encroachment cannot be avoided, transitions upstream and downstream of the structure should be hydraulically efficient to minimize changes to the adjacent channel features and to the floodplain. The stabilization of eroded low-flow channels or banks to protect property or infrastructure may also be part of the project design. As part of these efforts, fill in the historic floodplain should be minimized to the extent practical so that the flood storage function of the channel is preserved.

By respecting natural historic drainage patterns and flood-prone areas in early planning and implementing water quality and detention practices, drainageways and floodplains can be preserved that provide adequate capacity during storm events, that are stable, cost-effective and of high environmental value, and that offer multiple use benefits to surrounding urban areas. In the absence of historic beneficial features, it may be desirable to design natural functions into projects.

1.6.2 Minor Drainageways

In general, minor drainageways or minor channels are streams with contributing drainage basin areas less than approximately 130 acres. Minor drainageways may be reconstructed, relocated, or replaced with a storm sewer in combination with flood conveyance in the street network. However, the creation of vegetated surface channels is encouraged wherever practical in the minor drainageway network. These drainageways will typically be located upstream of detention storage facilities, and design flows will be based on developed conditions that produce flows much greater than undeveloped conditions. Although natural channel features may not be present in these types of channels, it is desirable to create naturalistic features including base-flow channels, low-flow channels and vegetated overbank areas to provide some of the beneficial functions of natural channels.

The amount of sediment transport in minor drainageways is expected to be limited when the upstream watershed has been developed and is stable. Sediment loads may be high while the drainage basin is under development, but this is unlikely to continue as the drainage basin becomes more developed.

1.6.2.1 Constructed Natural Channels

When adequate land is available, it is desirable to construct a modified channel that provides the benefits of natural channels such as flood storage, aesthetic benefits and habitat. Such “constructed natural channels” should be designed to emulate the functions of natural drainageways shown in Figure 12-1. Where practical, existing natural features should be incorporated into the design. For these types of projects, the primary design considerations are to emulate natural channels, avoid flooding of adjacent structures, provide stable channel conditions during flood flows, and pass sediment to reduce maintenance.

Stabilization improvements for the banks and overbank will depend on the design velocities and proposed ground cover. Grade control structures will normally be required for the low-flow channel. Grade control structures will also be required across the full channel section if overbank velocities exceed non-erosive levels.

This channel type includes grass-lined and composite channels, as defined by the UDFCD Manual, and may include bioengineered and wetland bottom channels, as well.

To complete the design of a constructed natural channel, low flows and flood flows must be analyzed to determine channel cross sections and slopes that will promote a stable channel. The evaluation of flood flows provides a delineation of the floodplain for land-planning purposes and provides the basis to maintain adequate freeboard for structures and adjacent developments. Flood flows also provide the basis for many types of scour analyses. If a baseflow channel is included in the design, baseflows must also be estimated. The presence of baseflows will also need to be considered if wetland bottoms are part of the design.

1.6.2.2 Constructed Channel

A channel that primarily provides flood flow conveyance may be necessary when upstream drainage basin conditions have already been significantly altered or are expected to be in the future, where the floodplain has already been significantly reduced, or where existing flooding is occurring. These channels may also be necessary where right-of-way is limited. Constructed channels will typically be fully lined with riprap, soil riprap, concrete, or manufactured linings. Some types of channel linings such as concrete, riprap and manufactured liners provide few benefits of a natural channel. The design of these channel types primarily depends on flood flows, but low flows and baseflows may be needed if sediment load passage is desired. The evaluation of flood flows provides the delineation of the floodplain for land planning purposes and provides the basis to maintain adequate freeboard at structures and for adjacent developments but will not normally be shown on the NFIP FIRMs for minor drainageways.

Most channel projects will be either a modified natural channel or a constructed natural channel. The conditions necessary to maintain a channel in fully natural conditions rarely occur in an urbanizing drainage basin and constructed channels are primarily intended to be used in retrofit situations where the upstream drainage basin is fully developed and there is limited right-of-way available. Table 12-1 summarizes the project conditions that generally determine the type of channel that is most appropriate.

1.7 Permitting and Regulations

Major drainage planning and design along existing natural channels can be a multi-jurisdictional process, and must comply with regulations and requirements ranging from local criteria and regulations to federal laws. Discussions with the relevant permitting authorities should be held early in the design development process and throughout construction to ensure that permitting and regulatory requirements are being met. Some of the more significant permitting processes required for typical channel projects are listed below. The list is not all-inclusive and additional permits may be required.

1.7.1 Floodplain Hazard Development Permit

A Flood Hazard Development Permit is issued by the Floodplain Administrator is required for all activities proposed within Federal Emergency Management Agency (FEMA) mapped floodplains. Refer to Chapter 5, Floodplain Management for additional information on floodplain permitting and regulations.

1.7.2 Section 404 Wetlands Permit

Streams designated by the U.S. Army Corps of Engineers (USACE) as “jurisdictional” under Section 404 of the Clean Water Act are subject to specific protections established during the 404 permit process. The 404 permit may impose limits on the amount of disturbance of existing wetland and riparian vegetation, may require disturbed areas to be mitigated, and may influence the character of proposed stream improvements.

Additionally, sites located upstream of water quality facilities may require protection in the form of temporary (construction) and permanent on-site water quality measures, including reducing directly connected impervious area before discharging to the waterway. Volume 3 of the UDFCD Manual describes on-site measures for water quality.

The USACE should be contacted early in the design process to determine if the activities will require a 404 permit.

1.7.3 Endangered Species Act

Construction of improvements along drainageways may also be subject to regulation under the federal Endangered Species Act. The USACE, as part of the 404 permit process, will typically coordinate with the U.S. Fish and Wildlife Service (USFWS) to assess potential impacts to threatened and endangered (T&E) species. The USFW may require a Biological Assessment to determine impacts and significant mitigation measures may be required if impacts are expected. In some areas, Block Clearances may be in place so that some environmental assessments are not necessary. The designer should determine whether a Block Clearance is effective for the project.

Additionally, T&E species must be addressed as part of the FEMA Conditional Letter of Map Revision (CLOMR) process. If T&E species will not be affected by work associated with a CLOMR, the applicant typically submits a letter with a finding of “no likely impact” that has received concurrence from the USFWS. If T&E species will be affected by work associated with a CLOMR, FEMA requires documentation that the appropriate permits have been obtained before they will issue a Letter of Map Revision (LOMR).

1.7.4 Erosion Control/Stormwater Management Permitting

Projects that will disturb one or more acres of land require the development of a Stormwater Management Plan (SWMP) and submittal of a Notice of Intent (i.e., application) to obtain certification of coverage under the Colorado Department of Public Health and Environment (CDPHE) General Permit for Stormwater Discharges Associated with Construction Activity.

2.0 Hydraulic Analysis

Hydraulic analyses and reporting must be adequate to confirm that applicable criteria are being satisfied by the proposed design. Roughness coefficients provided in Table 12-6 at the end of this chapter shall be used for hydraulic calculations. Additional guidance for roughness coefficients and parameters necessary to complete proper hydraulic analyses is provided in the Major Drainage Chapter of the UDFCD Manual.

2.1 HEC-RAS Analysis

Hydraulic analyses necessary to confirm that design criteria are satisfied can be complicated and often involve variable boundary conditions, various flow rates, a varying water surface profile, irregular channel geometry and crossing structures. Most project conditions require using the USACE's HEC-RAS computer software, which is available free from their website, to adequately assess project conditions. The application of the HEC-RAS computer software shall use model parameters described in this Manual or in the program documentation or justification shall be provided for values used that are not consistent with these documents.

2.2 Normal Depth Calculations

Generally, normal depth calculations may be used when these conditions are met:

- Channel geometry is uniform.
- Channel parameters are uniform.
- Design flows are steady.
- Backwater effects are not present.
- Water surface profile is uniform.
- Hydraulic boundary conditions are well known for all design flows.
- No structures are creating variable water surface elevations affecting flow in the channel.

UDFCD has created several spreadsheet programs that provide assistance in the evaluation of typical channel designs and crossing structures when project conditions are appropriate for normal depth calculations. These design aids may be used to complete project designs when appropriate.

3.0 Design Guidelines

Each reach or each segment of the project reach must be evaluated to determine the basin conditions that will influence its function within the drainage basin or watershed and the applicable design standards. Channel design requirements are determined by whether they are categorized as major or minor channels and by the particular characteristics of the project reach. The Major Drainage Chapter of the UDFCD Manual provides a thorough discussion of drainageway planning considerations, which should be referenced for guidance on urban effects, route considerations, and drainageway layout within a site.

3.1 Major Drainageways

The natural channel design criteria described herein and in the Major Drainage Chapter of the UDFCD Manual shall be used for all major drainageways unless otherwise approved by the City Engineer. Typical design elements included in a major natural channel design project are shown in Figure 12-4 and summarized as follows:

1. Create low-flow channel.
2. Establish a low-flow design longitudinal slope.
3. Utilize vegetated benches to convey overbank flow.
4. Slope-back and stabilize eroding banks.
5. Analyze floodplain hydraulics.
6. Evaluate potential impacts to aquatic ecology and incorporate measures to enhance biologic functions, where practical.
7. Undertake major drainageway plan improvements if required.

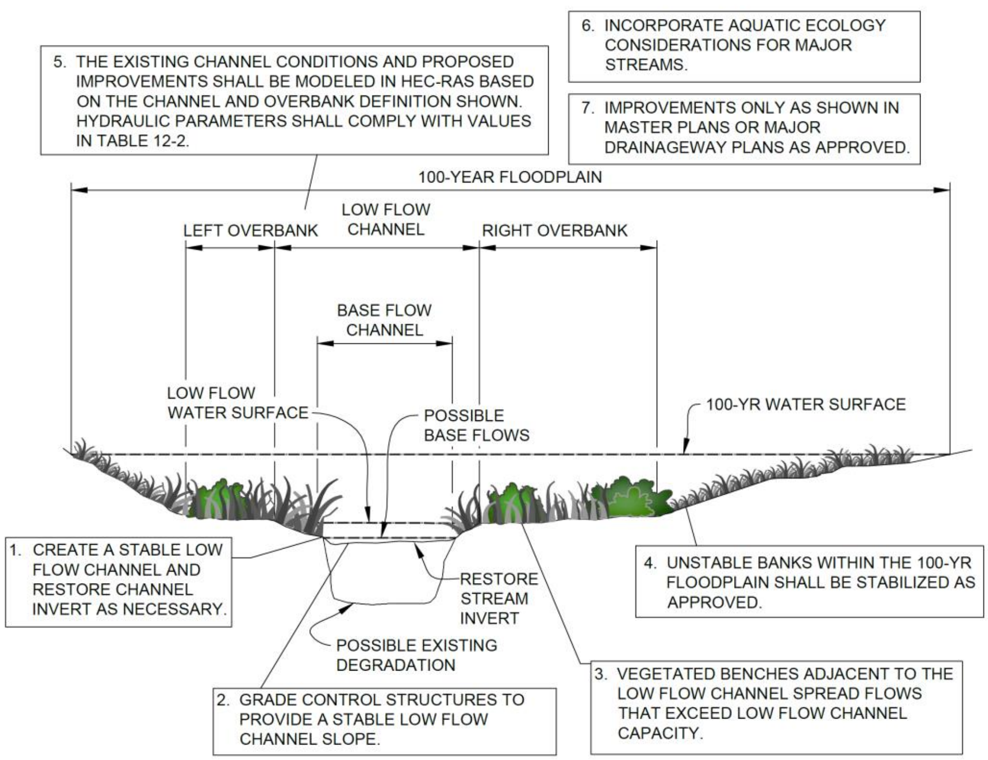


Figure 12-4. Design Elements Associated With Major Natural Drainageways

These seven steps are discussed in the following sections and comprise the recommended design approach for preserving, restoring, or modifying natural healthy drainageways. Designers shall address these seven elements and submit their proposed approach for drainageway stabilization for review and approval by the City.

3.1.1 Create Low-Flow Channel

One of the primary design tasks is to preserve or establish a low-flow channel that is appropriately sized in relation to the adjacent overbank geometry and the design low-flow rate. In general, shallow low-flow channels with adjacent well-vegetated overbank benches are best suited to spread-out and attenuate flood flows. The top of low-flow channel banks shall normally be established along the edge of the historic overbank. This may require filling degraded incised channels, excavating overbank benches adjacent to the low-flow 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 and restores the relationship between the low-flow channel and the floodplain, although filling generally will impact biota that are able to inhabit the degraded channel. Sometimes, it may be difficult to raise the invert of a degraded channel. Existing storm sewer outfalls may have been installed near the bottom of the incised channel and constrain how much the channel bed can be raised. It may be necessary to remove the downstream end of low storm sewer outfalls and reconstruct them at a higher elevation. Also, raising the invert may cause a rise in a critical floodplain elevation if the regulatory floodplain was based on the degraded channel condition (it is recommended that floodplains be determined for restored, not degraded channel conditions). There may be a need for compensatory excavation in other portions of the floodplain to offset rises in the floodplain caused by filling in the eroded low-flow channel.

The width of the low-flow channel shall approximate the width of the historic low-flow channel within the design reach or in stable reference reaches upstream or downstream. Normally, a low-flow channel exhibits some meandering and sinuosity in natural channels. Modified channels should feature a meander pattern typical of natural channels. Side slopes for low-flow channel banks shall be no steeper than 4H:1V for unlined banks. Lesser slopes are encouraged and may provide improved vegetative cover, bank stability and access. Allowable velocities for unlined low-flow channels are shown in Table 12-2. Criteria for lined channels are provided in the Major Drainage Chapter of the UDFCD Manual.

Table 12-2. Hydraulic Design Criteria for Natural Unlined Channels

Design Parameter	Erosive Soils or Poor Vegetation	Erosion Resistant Soils and Vegetation
Maximum Low-flow Velocity (ft/sec)	3.5 ft/sec	5.0 ft/sec
Maximum 100-year Velocity (ft/sec)	5.0 ft/sec	7.0 ft/sec
Froude No., Low-flow	0.5	0.7
Froude No., 100-year	0.6	0.8
Maximum Tractive Force, 100-year	0.60 lb/sf	1.0 lb/sf

[1] Velocities, Froude numbers and tractive force values listed are average values for the cross section.
[2] “Erosion resistant” soils are those with 30% or greater clay content. Soils with less than 30% clay content shall be considered “erosive soils.”

3.1.1.1 Baseflow Channel

If baseflows are present within the low-flow channel or are anticipated to be present in the future, it must be determined how the baseflows will be accommodated. Two common approaches include: 1) the invert of the low-flow channel can be shaped to accommodate a defined baseflow channel and a lower secondary overbank area or 2) the baseflows can be allowed to meander in the bottom of the low-flow channel without modifying the low-flow channel section. The baseflow rate may be based on available records from gage data, when available, but can be estimated based on field observations, seasonal hydrology and channel characteristics. The invert of the baseflow channel is typically unvegetated if a constant baseflow or frequent ephemeral flow is present, or vegetated with riparian or wetland species if baseflows are less frequent.

3.1.1.2 Wetland Bottom Channels

As described in the Major Drainage Chapter of the UDFCD Manual, there are circumstances where the use of a wetland bottom may be appropriate within the low-flow channel of a natural channel reach. Low-flow channels shall be designed with reference to the Major Drainage Chapter of the UDFCD Manual and the Treatment BMPs Chapter in Volume 3 of the UDFCD Manual. Riprap bank protection will generally not be required in wetland bottom channels. Freeboard requirements for wetland bottom channels shall be the same as those given for grass-lined channels.

3.1.1.3 Bioengineered Channels

Elements of bioengineered channels as described in the Major Drainage Chapter of the UDFCD Manual may be used in the design or stabilization of natural channels. Freeboard requirements for bioengineered channels shall be the same as those given for grass-lined channels.

3.1.2 Establish a Low-Flow Design Longitudinal Slope

Watershed development tends to cause channel degradation and a reduction in channel slopes. Therefore, the long-term stable slope of the low-flow channel is expected to be less than for undeveloped conditions and less than the longitudinal slope of the adjacent overbanks. To accommodate this anticipated change, grade control structures are required in the low-flow channel to create a “stairstep” profile to stabilize the low-flow channel and maintain the natural relationship between the low-flow channel and the floodplain. The estimated design slope determines how many grade control structures are required. A flatter design requires more grade control structures and increases costs. The spacing of drop structures depends on the original natural channel slope and the design slope necessary to stabilize the channel. The design and placement of grade control structures is described in Section 4.2, Grade Control Structures.

3.1.2.1 Ultimate Design Slope

Several methods have been developed to estimate channel slopes for ultimate (full) build-out upstream drainage basin conditions. When sediment loads are expected to decrease significantly and flows are expected to increase significantly, estimates of the ultimate stable slope tend to be flat. Even when flows are properly regulated through detention storage ponds upstream, the reduction in sediment load will still result in very flat estimates of the ultimate channel slope.

3.1.2.2 Interim Design Slope

When a long-term sediment supply may be present or when the time required for channels to reach their ultimate design slope can be long, methods that estimate an ultimate design slope based on no or a very limited sediment supply may be too conservative and increase the cost of channel stabilization. Therefore, intermediate design slopes may be used to construct fewer grade control structures initially if the need to ultimately construct additional structures is recognized and funded. Estimating design slopes in developing watersheds is complicated by difficulties in estimating interim sediment supplies, flows, channel dimensions and floodplain encroachment. Understanding these development impacts on channel slope can be important for financing long-term stabilization needs and designing effective structures.

Various methods for estimating interim channel slope changes as a result of development can be applied; however, due to the lack of availability of historic data, the uncertainty of changes in key input parameters (such as sediment load and flow), the experience required to apply them correctly and the uncertainty of the results, a geomorphologist or civil/water engineer with expertise in sediment transport should be consulted. There are a variety of methods that can be used for estimating a stable channel slope included historical data analysis, reference reach analysis, HEC-20 Incipient Motion Method, HEC-2 Equilibrium Slope Analysis, Lane's Form Relationship (Julien 2002), and detailed sediment transport analysis. A useful analysis by Henderson (1966) combined the Einstein-Brown bedload transport formula, Chezy flow resistance formula, and mass conservation for steady uniform flow, into a single proportionality where q_s and q are sediment transport rate and water discharge per unit width.

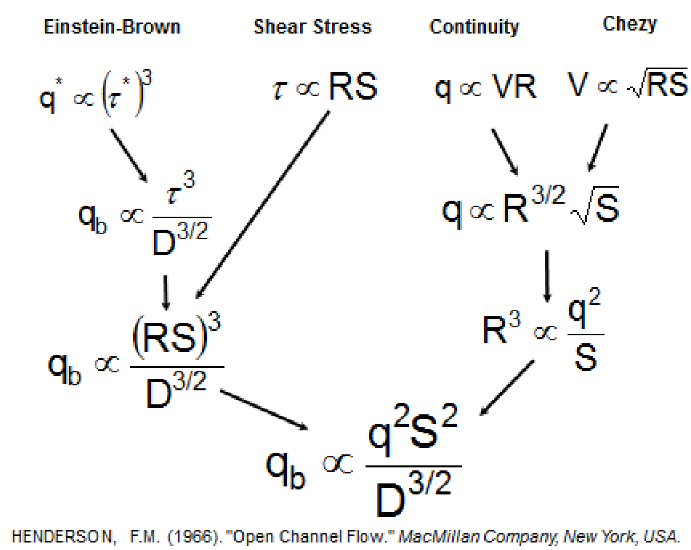


Figure 12-5. Sediment Transport and Discharge Relationship

For the purpose of interpreting past or future channel change, this relation can be solved for slope (S) and written twice as a ratio for the same reach at two different time periods.

$$\frac{S_2}{S_1} = \sqrt{\frac{q_{b2}}{q_{b1}}}\left(\frac{D_2}{D_1}\right)^{3/4}\left(\frac{q_1}{q_2}\right)$$

Equation 12-1

This relationship can be applied to the evaluation of channel change if D and q_b are the grain size and rate of sediment supply to the reach and q is the water supply to the reach. In this case, slope can be interpreted as the slope necessary to transport the sediment supplied (at rate q_b) with the available flow q. An increase in S ($S_2/S_1 > 1$) is not likely to be associated with a large increase in bed slope (which would generally take a very long time), but rather indicates a tendency for the channel to accumulate sediment and aggrade under a future watershed condition. A decrease in S represents degradation, or a tendency for the channel to incise. In most cases, little reliable information sediment supply is available. Nonetheless, this relation provides a useful relative estimate of the tendency of the channel to aggrade or degrade. Such an estimate may be at least as reliable (and perhaps more reliable) as that provided by more detailed calculations based on highly uncertain boundary conditions. Of particular interest is the delivery of coarse sediment that would be transported as bedload. Relatively coarse sediment (approximately the upper 35% of the bed material grain size distribution) has a disproportionately greater influence on stable channel slope compared to fine material. Therefore, the effect of reduced sediment delivery on channel stability depends primarily on the extent of imperviousness, channel erosion, and sediment trapping in areas of the watershed that yield coarse sediment, as opposed to the overall degree of development and impervious surfaces.

One of the challenges in applying equilibrium relationships based on sediment transport theory is the selection of appropriate dominant discharges to use in comparisons of pre- vs. post development conditions. Estimates of dominant discharge based on frequency analysis of peak flows do not directly account for the effects of urbanization on the frequency and duration of sediment transporting events.

Effective discharge analysis provides a more physically rigorous approach to quantifying the range of flows that are most responsible for transporting sediment and performing geomorphic work over engineering time scales. Such an approach allows designers to consider the full range of sediment transporting flows across the flow duration curve if continuous hydrologic data are available or can be generated through modeling for at least one, and preferably two to three decades of baseline and future conditions. Because it typically requires continuous hydrologic modeling (as opposed to single event), the effective discharge or “erosion potential” approach is more technically demanding and resource intensive. Nonetheless, for sand bed and labile channels the additional information this approach provides on cumulative sediment transport capacity across the full spectrum of sediment transporting flows is often essential for identifying a rational equilibrium slope.

If an applicant is considering sediment transport analysis to determine an interim channel slope, a meeting with the City Engineer should be held to review and agree on the methods of sediment transport/channel stability analysis before any formal submittal.

3.1.2.3 Estimating Historical Slopes

If field investigations or analyses of historical data indicate that channel conditions are currently in equilibrium, then measurements of the existing bed slope in the field or from topographic mapping can be used to provide a starting point for evaluating changes that may occur due to increased volume, flow rates and changes to sediment supply in the future. Channel slopes can vary along a stream reach so care must be exercised to utilize a slope value representative of the entire reach under design. Potential indicators of historical or on-going degradation include exposed infrastructure (pipe crossings or bridge foundations), extensive bank erosion and steep channel banks where the channel invert is below the roots of adjacent bank vegetation or has begun to expose them. Historical topographic mapping, FEMA studies, bridge or other structure design drawings can also provide insight on changing conditions. If field investigations or historical data indicate that channel conditions may not currently be in equilibrium, then data from a historical time when equilibrium conditions existed (aerial photos, maps, photos, etc.) should be used to estimate the historical slope. Potential sources of historical slope data include historical topographic mapping, previous studies and historical design drawings for structures. Stable reference streams or reference reaches can be used to estimate a stable slope. Geomorphic analysis of channel bank and valley slopes can be used to estimate channel slope for pre-development (undisturbed) conditions. The selection of reference reaches and geomorphic analysis of bank and valley slopes may be highly subjective and should be carried out only by qualified professionals with experience in geomorphology. The key is to select reference reaches that have approximately the same sediment supply, valley setting and boundary conditions. In many instances these criteria are only met just upstream if they are met at all. Downstream reference reaches are sometimes adjusted to the increased sediment delivery provided by unstable design reaches that are upstream. *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (USDA 1994) provides guidance on field measurement techniques.

3.1.2.4 Detailed Sediment Transport Analysis

A detailed sediment transport analysis may be appropriate when potential cost savings and available data are sufficient to justify the level of expertise and technical analyses required to produce reasonable results. These approaches to sediment transport analysis generally require using computer-based modeling. The most commonly used one-dimensional sediment transport model is HEC-6; however, most of its functions have now been incorporated into HEC-RAS. Other models that represent two-dimensional or even three-dimensional conditions are available, but are very computationally intensive and are not generally applicable for most routine channel design projects. The greater level of detail possible with a computer-based modeling approach includes:

- **Geometry:** Variations in channel geometry along reach can be modeled (mobile bed options only).
- **Sediment Data:** Sediment gradation data is utilized in the model and can be varied along the length of the channel reach depending on the number of samples taken. Most sediment transport models route sediment by size fraction and can simulate armoring (mobile bed option only).
- **Sediment Inflow Data:** A critical input into sediment transport models is the amount of sediment that is expected to enter the upstream end of the study reach or that might enter through tributaries along the study reach. This can be very difficult data to obtain or estimate.
- **Hydrology:** Measured or synthetic long-term hydrology (years) or hydrographs for single events can be discretized and modeled.

In spite of the greater level of detail, sediment transport modeling results can still have a wide margin of error and must usually be evaluated for reasonableness by comparisons with more conventional methods. Even with the greater level of detail, both data and modeling will have significant limitations and results should generally be interpreted only as indicating trends or ranges of potential change rather than exact future stream grades. The HEC-RAS Version 4.1 Hydraulic Reference Manual opens the discussion on sediment transport modeling by noting: “Sediment transport modeling is notoriously difficult. The data utilized to predict bed change is fundamentally uncertain and the theory employed is empirical and highly sensitive to a wide array of physical variables.” In keeping with this cautionary statement, uncertainty associated with modeling results should be considered when interpreting results. One of the most significant limitations of HEC-6/HEC-RAS modeling is that lateral bank erosion processes are not effectively modeled.

Detailed sediment transport modeling has some significant practical challenges, including:

- Considerable cost is typically required to develop model input data (hydrology, sediment, geometry) and to carry out the modeling itself.
- The method does not lend itself to standardized or “cookbook” approaches that can be concisely presented in a criteria manual. Considerable expertise and experience related to sediment transport modeling, hydrology and geomorphology are required.

In general, the importance of conducting a sediment transport analysis increases with higher sediment supply, the extent to which sand dominates the channel bed material, and the overall liability of the channel, i.e. flow energy relative to the erodibility of the channel boundary and floodplain materials. Estimates of sediment transport capacity based empirical relationships are often highly uncertain when the results are used as absolute magnitudes of sediment transport. However, application of a consistent and appropriate sediment transport relation can be very useful and quite accurate in estimating *relative* transport capacities among stream segments. This is especially true if a comparable supply reach in equilibrium and without intervening tributaries exists upstream of the reach of management interest. In this case, the relative sediment transport capacity of the supply reach versus the design reach can provide a robust estimate of a target design slope for re-establishing quasi-equilibrium.

3.1.3 Utilize Vegetated Benches to Convey Overbank Flow

For existing natural channels, vegetated benches often exist just above the tops of the eroded baseflow channel. When the historic natural floodplain is preserved and flows from upstream of the project reach are not expected to increase, it is likely that the undisturbed overbank areas of natural channels will be stable and require little or no stabilization. Raising the invert of degraded channels usually establishes a favorable overbank geometry. If necessary, benches can be excavated adjacent to the low-flow channel, especially if impacts to existing vegetation are minimal. It may be necessary to re-establish or supplement vegetation on the overbanks to build up a sturdy, durable cover to help retard flood flows and resist erosion. Except for the delineation of the floodplain limits, the hydraulic characteristics of this portion of the natural channel should not be a design consideration when the natural floodplain is stable and preserved.

3.1.4 Stabilize Eroding Banks

Steep unstable banks existing within the 100-year floodplain should be sloped back and stabilized. On a plan-view topographic map, designers shall indicate the location, height and existing slope of any unvegetated, steep, or otherwise unstable banks within the 100-year floodplain, along with the proposed approach for stabilizing the banks. This may occur where the low-flow portion of the channel has meanders that impinge on the outer channel banks.

The designer shall consider the existing bank conditions and angle of attack, the estimated potential for future erosion, and the proximity of infrastructure that could be impacted by the bank erosion as a basis for determining the appropriate method for bank stabilization. Other channel characteristics such as channel geometry, longitudinal slope, existing vegetation, underlying soils, available right-of-way and expected flow conditions shall be considered and analyzed with respect to the various potential improvements.

Unstable banks shall be protected using one of the following approaches.

1. **Sloping Back Banks:** Steep, unstable banks shall be cut back to a flatter slope and revegetated. The maximum permissible slope shall generally be 4H:1V (horizontal:vertical). Reducing bank slopes to 6H:1V or flatter will assist in the establishment and viability of vegetation, the stability of channel banks and accessibility of the waterway for recreation. Designers are encouraged to utilize flatter slopes whenever possible. In some locations, right-of-way constraints may dictate steeper slopes. In such areas, slopes up to 3H:1V may be permitted with appropriate slope protection and approval.

2. **Riprap Bank Protection:** Riprap bank protection is widely used to stabilize channel banks along the outside of existing channel bends and along steep banks that cannot be graded back

sufficiently due to right-of-way constraints, where flow velocities are too high, or where overbank grades are too steep. Riprap bank protection shall be designed in accordance with the Major Drainage Chapter of the UDFCD Manual. All riprap bank protection shall consist of soil riprap that is buried with topsoil and revegetated.

The riprap need only extend up the slope to where shear stresses do not exceed those for natural unlined channels as defined in Table 12-2. By applying those allowable shear stress limits to the equation for shear stress, the vertical distance from the 100-year water surface to the upper limit of the riprap layer can be calculated as follows:

If $\tau = \gamma dS$, then

$$d = \tau/\gamma S \qquad \text{Equation 12-2}$$

For Erosive Soils, $\tau = 0.6\ \text{lb/sf}$ and if $\gamma = 62.4\ \text{lb/cf}$, then

$$d = 0.0096/S \qquad \text{Equation 12-3}$$

For Erosion Resistant Soils, $\tau = 1.0\ \text{lb/sf}$ and if $\gamma = 62.4\ \text{lb/cf}$, then

$$d = 0.0160/S \qquad \text{Equation 12-4}$$

Where:

d = vertical distance below 100-year water surface

S = channel overbank slope in ft/ft

3. **Bioengineered Bank Protection:** Experience with the application of bioengineering techniques to protect channel banks is growing along the Colorado Front Range. Bioengineering techniques are discussed in the Major Drainage Chapter of the UDFCD Manual.

3.1.5 Analyze Floodplain Hydraulics

The floodplain associated with existing or modified natural channels shall be analyzed using HEC-RAS to delineate the 100-year floodplain and evaluate flow velocities to assess drainageway stability based on flow rates for the range of design flows. It is important to analyze floodplain hydraulics based on conditions that are likely to cause the greatest resistance to flow and the highest water surface elevations in the short term and over time. Some of these conditions may include the following:

- Increased baseflows and runoff from development that promote increased growth of wetland and riparian vegetation, making drainageways hydraulically rougher.
- Stream restoration work that raises the bed of incised channels to levels that existed prior to degradation or flattens channel slopes.
- Upstream bank erosion or watershed erosion, flatter slopes, and increased channel vegetation that lead to sediment deposition and channel aggradation, raising streambed and floodplain elevations.

An accurate delineation of the floodplain is also necessary for laying out development projects and setting lot and building elevations adjacent to the floodplain according to the freeboard requirements defined in Chapter 5, Floodplain Management. For facilities that are not structures (typically not requiring a building permit) such as roadways, utility cabinets, parks and trails improvements, etc., a minimum of 1 foot of freeboard is desirable. Assessments of freeboard at bends shall take into account super elevation calculated in accordance with the Major Drainage Chapter of the UDFCD Manual. The required freeboard should be contained within a floodplain tract and/or easement.

Incised or eroded channels shall not be analyzed based on their existing geometry, but on the geometry representative of a restored natural channel, as illustrated in Figure 12-1. Otherwise, the floodplain may be inappropriately low, constraining future restoration efforts such as installing grade control structures that raise the channel bed back to earlier conditions.

3.1.5.1 Floodplain Encroachments

Floodplain encroachments that reduce natural channel storage and increase downstream flows or velocities are discouraged. However, when encroachments are approved and proper documentation is submitted and approved as described in Chapter 5, Floodplain Management, channel hydraulics must be fully analyzed to ensure that the remaining natural channel features or designed low-flow channel are stable during flood flows. To ensure that encroachments into natural floodplains are stable, the criteria in Table 12-2 shall be confirmed through a hydraulic analysis of the low-flow channel and the residual floodplain during the 100-year flood event.

3.1.6 Consider Aquatic Ecology

When streams or major drainageways, such as Fountain Creek, have conditions that are favorable for supporting fish, additional consideration should be given to the baseflow and low-flow channel designs to provide conditions that are consistent with good aquatic ecological conditions, fish habitat and fish passage.

The Colorado Division of Wildlife currently lists 14 species of fish as endangered or threatened at the state or federal level. An additional 9 species are listed as state species of concern (CDOW 2011). The majority of these species are small plains fish, whose natural habitat includes the plains and transition zone stream systems throughout the Front Range where urbanization impacts have been greatest. Several species of cutthroat trout are also included on the list. Trout are most prevalent in the foothills and higher elevations where colder water temperatures and coarser substrates are found.

Aquatic habitat is degraded in a variety of ways by watershed urbanization and stream modification. Potential impacts include water quality, water quantity, loss of bank vegetation, bank erosion and channel invert degradation. Implementation of the natural stream design principles presented in this Manual can significantly help preserve or improve aquatic habitat. Important aquatic habitat design considerations include:

1. **Water Temperature.** Water temperature is one of the most important factors in determining the distribution of fish in freshwater streams (FISRWG 2001). Feeding and spawning activities are often keyed to water temperatures, and high water temperatures can be lethal to some species. Often in degrading stream systems, bank erosion results in a loss of perimeter vegetation and a widened channel bottom that produces shallow-flow depths. Limiting baseflow channel widths to increase typical flow depths and providing bank vegetation for shading can reduce solar heating of the water.

2. **Cover and Refuge.** Providing cover in the form of overhead vegetation, boulders, large woody debris, pools and other irregular features provides fish with spawning areas, protection from predation, and habitat for species that are critical to the food chain. Channel design elements

that can contribute to enhanced cover include pool and riffle sequences, a variety of vegetation types along the channel edge, variations in baseflow channel geometry, scour holes, groupings of boulders, and woody debris such as root wads and logs in various configurations. Several resources for the design of fish habitat enhancement structures are included in the references for this chapter.

3. **Habitat Diversity.** Diversity of habitat and hydraulic conditions allows for a greater diversity of species and a richer ecosystem. Channel designs can incorporate riffles, pools, small drops, boulders, large woody material, changes in channel geometry and a variety of riparian plant types to create diversity.

4. **Water Quality.** High organic matter and chemical content is common in urban stream systems. Channel designers typically have limited ability to change or rectify these conditions; however, identifying and understanding the characteristics of these sources should be incorporated into the project design. Sources typically include wastewater treatment plant discharges and urban runoff carrying various chemicals, fertilizers, yard cuttings and other organic matter. High organic content can lead to low dissolved oxygen levels and the death of aquatic organisms. Shading of channels with vegetation to reduce water temperatures and riffle and drop structures to induce aeration can help with this problem.

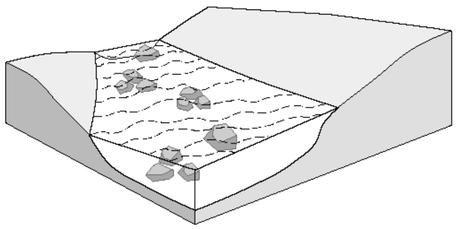
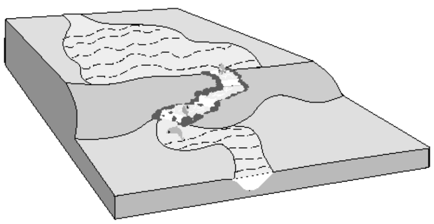
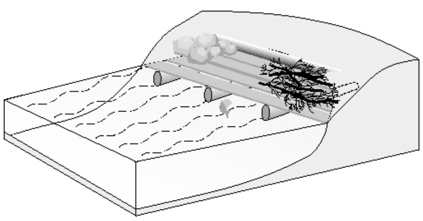
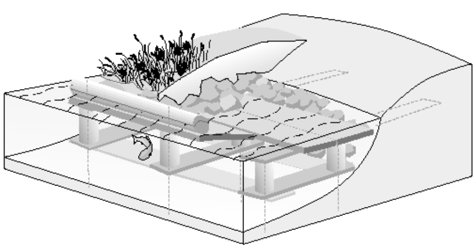
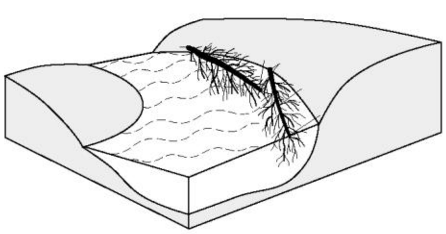
5. **Substrate.** Sand and silt substrates are generally the least favorable alluvial materials for supporting aquatic organisms and support the fewest species and individuals (FISRWG 2001). Smooth bedrock surfaces devoid of alluvium, which exist in many degraded stream systems along the Front Range, are even less favorable. Raising degraded channel inverts with grade controls can naturally restore alluvial channel bottoms. Riffles and other rock structures can also add diversity to the substrate.

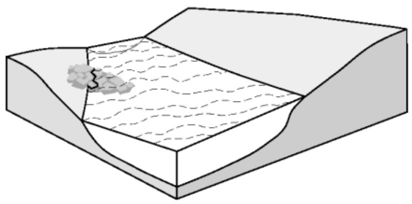
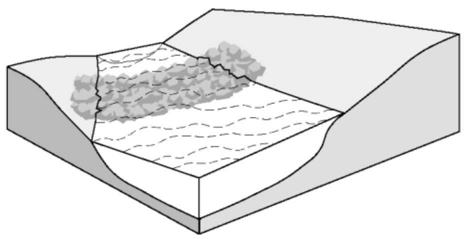
6. **Hydrology.** Both increases and decreases in natural channel flows can have adverse impacts on aquatic habitat. Withdrawals of water for agricultural, industrial and municipal uses can reduce stream flows to essentially dry conditions at some times of the year. Increases in flows from lawn watering return flows, runoff associated with increased imperviousness, and wastewater treatment plant discharges increase velocity and shear and can erode channel banks and bottoms removing habitat features and cover. Higher velocities can impede migration and reduce the portion of a stream that is habitable by native plains fish species, which are generally weak swimmers.

7. **Stream Crossing Structures.** Most plains fish species, unlike salmon and trout species, are relatively weak swimmers and have limited or no jumping capability. Because of this, stream crossing structures, such as grade controls, culverts or bridges, which create high velocity flows or small discontinuities in the water surface, can be an impediment to migration. Most plains fish species have ranging and migration for spawning behaviors that make stream connectivity critical to their survival (Ficke and Myrick 2010). Disconnecting stream segments with impassible hydraulic structures results in genetic isolation, which also degrades species viability. Two recent studies at Colorado State University on plains fish swimming performance and fish passage design recommendations are provided in the list of references for this chapter.

Maintaining natural stream systems and corridors is the best way to provide adequate and sustainable habitat for fish. Where restoration is taking place or where natural stream functions are limited by urbanization impacts, structures specifically constructed to enhance fish habitat may make sense. Table 12-3 provides a summary of the basic techniques most commonly employed, when they may be appropriate and cautions in their use. The References Chapter of this manual contains additional information on these types of structures.

Table 12-3. Fish Habitat Structures

Technique	Application/Description
	**Boulder Clusters** • Groups of boulders placed in the baseflow channel to create cover, scour holes and velocity refuges. • Not appropriate in sand-bed streams (boulders tend to sink into the scour holes they create). • Use caution with placement - can cause bank erosion. • Not appropriate in aggrading or degrading streams. • Can promote bar formation in high bed-load streams.
	**Fish Passages** • Variety of structure types intended to provide passage for fish over man-made obstructions such as dams or grade controls. • Typically expensive. • Can be rendered ineffective by stream invert degradation.
	**Log/Brush/Rock Shelters** • Log, stone and/or brush shelters constructed at the bank toe to provide overhead cover. • Inappropriate in streams where invert is aggrading or degrading. Stable invert and water levels are required. • Inappropriate where heavy bed-load movement exists. • Not recommended in areas of highly unstable banks.
	**Lunker Structures** • Submerged cells constructed of heavy wood and stone at the bank toe to provide cover for fish. • Typically expensive. • Inappropriate in streams where invert is aggrading or degrading. Stable invert and water levels are required. • Inappropriate where heavy bed-load movement exists. • Not recommended in areas of highly unstable banks.
	**Tree Cover** • Felled trees secured to bank to provide habitat, velocity refuges and bank protection. • Inexpensive if trees available on-site. • Must be adequately anchored to prevent transport and possible damage to downstream structures during floods. • Have the potential to cause bank erosion.

Technique	**Application/Description**
	**Wing Deflectors** • Log, root wad or stone protrusions from the channel bank providing diversity, cover and velocity refuges. • Can help stabilize banks by slowing and deflecting flows. • Failure from undermining or erosion of banks possible especially in sand-bed streams.
	**Sills and Grade Controls** • Log, stone or concrete structures placed across channel. • Can control invert degradation, improve bank stability, restore alluvial bottom, provide habitat diversity, cover and velocity refuges. • Can impede upstream fish movement. • Can be undermined, especially in sand-bed streams. • Crest design and orientation important to avoid wide shallow flows, bank erosion and upstream aggradation.

3.1.7 Undertake Major Drainageway Plan Improvements if Required

In addition to the six mandatory design elements discussed in Sections 3.1.1 through 3.1.6, additional major drainageway plan improvements may be required on a case-by-case basis.

3.2 Minor Drainageways

Constructed natural channels, including grass-lined channels or composite channels, shall generally be used for minor drainageways. However, constructed channels that are riprap-lined, concrete-lined or manufactured lining types may be necessary due to project constraints. The use of conduits is discouraged and must be approved on a case-by-case basis.

3.2.1 Constructed Natural Channels

Because the upstream drainage basin conditions are expected to change dramatically for minor drainageways, resulting in higher flows and low sediment loads, it is likely that creating a naturalistic channel design will require significant regrading of unimproved channels. This will generally require the removal and reestablishment of natural vegetation, rather than its preservation.

For constructed drainageways designed to emulate unlined natural channels, the parameters in Table 12-2 shall be achieved for both the low-flow and the 100-year event. Existing natural features should be protected to the extent practical. Hydraulic modeling shall be based on the channel and overbank definition shown in Figure 12-3 and on the roughness information identified in Table 12-6. Constructed natural channels must be analyzed for both higher velocity conditions, when projects are newly completed and vegetation may not have matured, and for higher flood potential and capacity conditions, when vegetation has fully matured and creates the greatest resistance to flow.

3.2.2 Grass-Lined Channels

Grass-lined channels are an option for minor drainageways, especially where the tributary area is relatively small and minimal baseflows are expected. Sod-forming native grasses suited to wetter conditions are recommended for grass-lined channels. See Chapter 14 for vegetation recommendations. If irrigated bluegrass sod is proposed, a small baseflow channel shall be provided and vegetated with the wetter, sod-forming native grasses. Hard-lined baseflow channels are not desired in grass-lined channels. Grade control structures or rock stabilization in the bottom of the channel may be necessary if velocities or longitudinal slopes exceed the values in Table 12-4.

Design criteria and guidance for grass-lined channels are provided in the Major Drainage Chapter of the UDFCD Manual, in addition to the key design features summarized in Table 12-4.

Table 12-4. Hydraulic Design Criteria for Grass-Lined Constructed Natural Channels

Design Item	Grass: Erosive Soils	Grass: Erosion Resistant Soils
Maximum 100-year velocity	5.0 ft/s	7.0 ft/s
Minimum Manning's "n" for capacity check	0.035	0.035
Maximum Manning's "n" for velocity check	0.030	0.030
Maximum Froude number	0.5	0.8
Maximum 100-year depth outside low-flow zone	5.0 ft	5.0 ft
Maximum channel longitudinal slope	0.6%	0.6%
Maximum side slope	4H:1V	4H:1V
Maximum centerline radius for a bend	2 x top width (200 ft min.)	2 x top width (200 ft min.)

[1] Velocities, Froude numbers and tractive force are average values for the cross section.
[2] "Erosion resistant" soils are those with 30% or greater clay content. Soils with less than 30% clay content shall be considered "erosive soils."

3.2.3 Composite Channels

Composite channels include a low-flow channel and a constructed floodplain that will normally convey flows much greater than undeveloped flows. The Major Drainage Chapter of the UDFCD Manual describes circumstances where the use of a composite channel may be appropriate and provides guidance for their design.

3.2.4 Wetland-Bottom Channels

There are circumstances where the use of a wetland-bottom channel may be appropriate. These channels are a special case of composite channels where it is intended that the lower portion of the low-flow channel be designed to support wetland plants. Guidance for wetland-bottom channels is also provided in the Major Drainage Chapter of the UDFCD Manual and Treatments BMPs Chapter in Volume 3 of the UDFCD Manual.

3.2.5 Bioengineered Channels

When bioengineered channel treatments are included in composite channels, they shall be designed using the guidance provided in the Major Drainage Chapter of the UDFCD Manual.

3.2.6 Constructed Channels

Constructed channels may be necessary when the upstream drainage basin is highly developed and design flows are significantly greater than undeveloped flows, when sediment loads are low, and where available right-of-way is restrictive. These channels retain few of the benefits of natural channels and primarily function as flood conveyance structures. Because these channels are generally steep and the flow is confined, design velocities tend to be higher, requiring a hardened channel lining to maintain stability. However, there are maximum velocity limitations on these channels; therefore, drop structures must be used to reduce design slope and lower velocities to acceptable limits. These structures will typically be designed for 100-year flows and will most often be lined with riprap, soil riprap, or concrete, but may also be lined with manufactured systems.

Because these types of channels eliminate any overbanks or floodplains, base-flow channels or low-flow channels do not normally provide a benefit. The use of base-flow or low-flow channels in these types of channels can help to pass sediment through the system and reduce maintenance requirements if sediment loads are present; however, in many cases, the available sediment load will be limited.

3.2.6.1 Riprap-Lined and Concrete-Lined Channels

The use of plain (not buried) riprap-lined or concrete-lined channels is generally discouraged, but they will be considered for minor drainageways on a case-by case basis. Design criteria for concrete-lined and riprap-lined channels are provided in the Major Drainage Chapter of the UDFCD Manual. Freeboard requirements for riprap and concrete-lined channels shall be the same as those given above for grass-lined channels. Additionally, if supercritical flow is present in concrete-lined channels, freeboard shall be computed in accordance with the Major Drainage Chapter of the UDFCD Manual.

4.0 Grade Control Structures

Grade control structures provide energy dissipation and are used to establish flatter design slopes and moderate flow velocities in the upstream channel reach. Table 12-5 provides typical maximum drop heights for grade control structures. Grade control structures are normally constructed as hardened drop structures, but may be implemented in other forms, such as rock riffles, with approval. Common approaches shall be considered when implementing grade control structures, as discussed below.

Table 12-5. Grade Control Drop Height Limits

Capacity of Grade Control Structure	Maximum Drop Height (feet)
Low-flow Discharge	1.5
Between Low-flow and 100-year	2.5
100-year and Greater	4.0

4.1 Low-Flow Drop Structures

Low-flow drop structures are grade control structures that extend only across the low-flow channel to provide control points to limit degradation at specific locations and to establish flatter thalweg slopes. During a flood event, portions of the flow will circumvent the structure and travel in the overbank portion of the channel. These structures are only appropriate for natural channel types or for constructed natural channels when overbank conditions do not exceed the allowable limits so that full-width drop structures are not necessary. When overbank conditions exceed allowable limits for vegetated channels in Table 12-2, it will be necessary to design a full-width, 100-year drop structure as described in Section 4.2.

Typically, low flows are contained within the hardened portion of these structures and fill the full cross section of the structure without freeboard. Low-flow drop structures are not appropriate within completely incised floodplains or very steep channels where the velocities shown in Table 12-2 cannot be achieved.

To provide a stable structure, secondary design flows must also be evaluated. The secondary design flow is the flow that causes the worst condition for flow around the sides of the structure, stability within the structure, or as flows return back into the low-flow channel downstream (i.e., a 5-year, 10-year, or 100-year event). Designers must evaluate site-specific hydraulics to determine the extent of surface protection and where in the cross section it may be appropriate to transition to softer types of protection such as vegetated soil riprap. One approach to analyze the hydraulics of low-flow drops is to estimate unit discharges, velocities and depths along overflow paths. The unit discharges can be estimated at the crest or critical section for the given total flow. Estimating the overflow path around the check can be difficult and requires judgment. The flow distribution option in HEC-RAS may be used to assist in evaluating minimal or reasonable damage to the floodplain below.

The minimum crest depth (from the invert of the crest to the top of the structure at the beginning of the overbank area) for low-flow drop structures is 1.5 feet. The maximum drop height of low-flow channel grade control structures shall generally be limited to 1.5 feet.

Seepage control is also an important consideration because piping and erosion under and around these structures can contribute to their failure. It is essential to provide a cutoff wall that extends laterally at least 5 to 10 feet into undisturbed bank and that has a depth appropriate to the profile dimension of the drop structure.

Check structures described in the UDFCD Manual are implemented within the UDFCD as temporary devices with the expectation that drop structures will replace the check structures as the channel degrades. This approach is not appropriate when long-term improvements must be completed with limited capital funds or for cost estimates for long-range basin plans. Rather than constructing temporary check structures, it is more appropriate to construct fewer permanent drop structures within a project reach with the goal of adding additional structures later. However, this approach is only appropriate if a funding source is available for completing the later improvements. In any case, channels must be designed for ultimate conditions so that adequate funding can be identified for permanent channel improvements as needed.

Design guidance for low-flow grade-control structures is provided in the Hydraulic Structures Chapter of the UDFCD Manual.

4.2 Full-Channel-Width 100-Year Drop Structures

Full-channel-width drop structures are structures that are designed to convey the major flood flow within the structure and to provide a stepped invert profile so that channel velocities (both in the low-flow channel and in the overbank area) do not exceed allowable limits. These structures are necessary in constructed natural channels and constructed channels when 100-year flood flow velocities exceed allowable limits. Each drop structure location is unique and designers should evaluate the required extent of hardened drop structure materials across the floodplain for each individual structure. Often grouted boulders do not need to extend to the limit of the 100-year floodplain, even where channels are incised to some degree and the floodplain has been encroached upon. Shear and velocity values typically decrease with increasing distance from the main channel; therefore, transitions to soil riprap and then to vegetation may be feasible. These floodplain hydraulic characteristics should be evaluated and hardened surfaces and soil riprap used only where necessary to minimize costs and enhance aesthetic and environmental qualities.

The Hydraulic Structures Chapter of the UDFCD Manual provides drop structure design considerations, procedures and details, discussion regarding various types of structures, and construction considerations.

4.2.1 Constructed Natural Channel Drop Structures

When deep channel incision and/or development in the floodplain or increased flood flows have already occurred, the potential for channel restoration may be limited. In such cases, drop and grade control structures may be necessary to convey the major flood without causing significant damage. The maximum allowed height for such structures is 4 feet. This criterion has been established to limit channel incision, minimize the amount of bank stabilization required, avoid developing excessive kinetic energy, avoid lowering of the groundwater table, and minimize the obtrusive appearance of massive structures.

In addition to these standard criteria, designers should consider the necessary extent of grouted rock or other hardened surface material. It may not be necessary for the hardened surface to extend across the entire 100-year waterway to provide 100-year protection. Instead it may be possible to transition to softer treatments such as vegetated soil riprap at the point in the floodplain where velocities and shear stresses are sufficiently reduced according to the criteria defined in Table 12-2.

4.2.2 Constructed Channel Drop Structures

Constructed channel drop structures are placed in channels that are fully hardened and under significant hydraulic stresses. These conditions require full-width, 100-year drop structures and shall be designed in accordance with the guidance provided in the UDFCD Manual.

4.3 Drop Structure Types

The use of drop structure types and configurations that are functional, natural-looking, provide for fish passage, and blend-in with the drainageway and surrounding environment are encouraged. The most common type of drop structure in Colorado’s Front Range communities is the grouted sloping boulder drop structure. Grouted boulders can be used to develop more unique, natural looking configurations such as a horseshoe-arch shape or stepped configurations. Other drop types that have been used in the region include sheet pile drops, sculpted concrete drops, and soil cement drops. The sculpted concrete drops have become more popular for aesthetic reasons, particularly in upland prairie settings. The concrete is shaped, sculpted, and colored with earth tones to emulate natural rock outcroppings. Use of the following drop structure types is preferred:

- Grouted sloping boulder
- Grouted boulder in natural configurations
- Sculpted concrete.

Design guidance, detailed design criteria, and construction details have not been developed by the UDFCD for sculpted concrete drop structures. It is the responsibility of the design engineer to develop and provide detailed construction drawings, based on previous experience in the design of sculpted concrete drop structures or review of past designs that have been constructed in the Denver Metro area.

The use of soil cement and roller-compacted concrete drop structures may be allowed, but only on a case-by-case basis. Steady baseflows can quickly erode soil cement, especially when there is significant sediment being transported. Soil cement structures may be provided with a hardened low-flow channel to prevent erosion or should be reserved for ephemeral or intermittent channels. Specifications and construction quality control needed for soil cement and roller-compacted concrete are extensive and generally must be in accordance with standard specifications developed by organizations such as the Portland Cement Association.

Vertical drops greater than 2 feet in height are not permitted for safety reasons. In dry conditions, the vertical face presents a fall hazard. Under flowing conditions, reverse flows on the downstream face can form dangerous “keeper” hydraulic conditions. Vertical drops greater than 2 feet in height may be permitted, but drop heights should consider fish passage if the stream supports a fishery. Additionally, they should be constructed of natural or natural appearing materials such as grouted boulders. The use of sheet pile or cast-in-place concrete walls for these structures is generally discouraged for aesthetic reasons.

Other methods of constructing low-flow drop structures, including rock riffles, ungrouted boulder drops and boulder cross vanes, may also be acceptable when floodplain and hydraulic conditions are appropriate for their use and when properly designed. These types of structures will generally not be appropriate in situations where there has been significant encroachment into the floodplain, where an incised channel condition will exist, or where urbanization has significantly increased peak flood flows. Approval of the use of such structures will be on a case-by-case basis.

Where fish passage is a concern at grade control structures, additional information can be found in the references provided at the end of this chapter and in the Colorado Springs Manual. Designing to accommodate fish passage must first identify target species and then establish adequate flow depths, meet maximum allowable flow velocities and distances between refuges and meet maximum vertical drop heights (if any). A variety of configurations are possible, but given the very limited swimming and jumping capabilities of plains fish, use of separate fishways or ramps that allow steeper slopes across the main channel portion of a drop structure will often be the most economical approach. In addition to the swimming and jumping performance criteria previously mentioned, the design of separate fishways requires careful attention to flows and a crest design that ensures the entrance to the fishway has adequate depth and does not become obstructed by sediment or debris over time. A high level of care, attention to detail, and supervision will generally be required during construction of any fish passable structure to ensure the constructed passage meets stringent criteria.

4.4 Drop Structure Placement

The distance between drop structures varies with the difference between the bank slope and the design slope and the height of the upstream structure. The distance between drop structure crests is determined by dividing the height of the upstream structure by the difference between the top of bank slope and the invert design slope. By intersecting the design slope with the toe of the face of the upstream drop structure, the proper relationship between the drop structures will be maintained. Drop structures must extend down below the design slope to provide protection from local scour and long-term degradation that might extend below the estimated design slope.

Drop structures may also need to be placed where necessary to protect upstream infrastructure or to control water surface elevations to divert flood flows into detention facilities or diversion channels.

5.0 Revegetation

Revegetation efforts and selection of appropriate vegetation are critical elements of all channel design projects. Chapter 14 of this Manual provides guidelines for revegetation efforts. These guidelines shall be followed for all major and minor drainageway design projects.

6.0 Easements, Ownership and Maintenance

6.1 Easements

Drainage easements are required in order to allow access for proper maintenance and operation of open channels. Drainage easements shall be granted to the party responsible for inspection and maintenance purposes, and shall be shown on the drainage plan, final plat and final development plan. Drainage easements shall be kept clear of impediments to flow and access.

Minimum easement widths shall provide for conveyance of design flow rates, the required freeboard, and access for maintenance. Narrow existing channels and high flow velocities merit consideration of easements that may be wider than the existing floodplain limits or minimum values. A specific exception shall be any banks allowed to remain in place at a slope steeper than 4H:1V. Such banks shall have the easement line set back from the top of the bank to allow for some lateral movement or future grading improvements to the bank. The easement line shall be no closer than the intersection of a 4H:1V line extending from the toe of the slope to the proposed grade at the top of the bank, plus an additional width of 15 feet for an access bench if access is not feasible within the floodplain.

6.2 Ownership

To ensure that drainageways and the associated conveyances are adequately preserved and properly maintained, all major and minor drainageways that convey flows from other properties should be placed on tracts of land owned by a public entity (e.g., special district, homeowner’s association, county, and other regional agencies). If the drainageway runs through private land, the City will require a drainage easement for any improvements to the reach.

6.3 Maintenance

6.3.1 Design for Maintenance

Open channels and swales should be designed to minimize maintenance requirements and efforts and with adequate maintenance access to ensure continuous operational capability of the drainage system. When provisions for maintenance access are being developed, consideration must be given to the potential maintenance activities and the equipment normally used to perform those activities. Designs that rely on the establishment of a vegetative cover, such as bioengineered or grass-lined channels, must include a plan for establishment, including temporary or permanent irrigation of the area.

Continuous maintenance access, such as with a trail, shall be provided along the entire length of all major drainageways. Depending on the channel size, tributary area, expected maintenance activities, and the proximity of local streets and parking areas, a continuous stabilized trail may be required along minor drainageways. The stabilized maintenance trail shall have a stabilized surface at least 8 feet wide and a minimum clear width of 12 feet for a centerline radius greater than 80 feet and at least 14 feet for a centerline radius between 50 and 80 feet. At drop structures, the minimum clear area shall be 20 feet. The minimum centerline radius shall be 50 feet. The maximum longitudinal slope shall be 10 percent. The responsible party may require paving with asphalt or concrete, otherwise, as a minimum the road shall be surfaced with 6 inches of CDOT Class 2 road base. Under certain circumstances, adjacent local streets or parking lots may be acceptable in lieu of a trail for major drainages.

6.3.2 Maintenance Responsibility

Maintenance responsibility lies with the owner of the land, except as modified by specific agreement. Maintenance responsibility shall be delineated on the Final Plat and described in the Final Drainage Report, or right-of-way conveyance documents. Maintenance of an open channel includes routine maintenance such as periodic sediment and debris removal. Channel bank erosion, damage to drop structures, low-flow channel deterioration, and other channel degradation must be repaired to avoid reduced conveyance capability, unsightliness, water quality issues, safety issues, and ultimate failure. Maintenance operations shall be in accordance with the approved Operations and Maintenance Manual (O&M Manual) for the project.

Table 12-6. Roughness Coefficients

Channel Description	Roughness Coefficient (n)		
	Minimum	**Typical**	**Maximum**
Natural Streams (top width at flood stage <100 feet			
1. Streams on Plain			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as c, but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain Streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. Bottom: gravels, cobbles, and few boulders	See Jarrett's equation*		
b. Bottom: cobbles with large boulders			
Major Streams (top width at flood stage > 100 feet)			
1. Regular section with no boulders or brush	0.025		0.060
2. Irregular and rough section	0.035		0.100
Grass Areas **	**Flow Depth =0.1-1.5 ft		Flow Depth > 3.0 ft
1. Bermuda grass, buffalo grass, Kentucky bluegrass			
a. Mowed to 2 inches	0.035		0.030
b. Length = 4 to 6 inches	0.040		0.030
2. Good Stand, any grass			
a. Length = 12 inches	0.070		0.035
b. Length = 24 inches	0.100		0.035
3. Fair Stand, any grass			
a. Length = 12 inches	0.060		0.035
b. Length = 24 inches	0.070		0.035

*Jarrett's equation: $n = 0.39 S_f^{0.38} R^{-0.16}$, where S_f equals friction slope and R equals the hydraulic radius.
** The n values shown for the grassed channel at the 0.1- to 1.5-ft depths represent average values for this depth range. Actual n values vary significantly within this depth range. For more information, see the *Handbook of Channel Design for Soil and Water Conservation* (SCS 1954).