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701 INTRODUCTION

Water that is conveyed so that the top surface is exposed to the atmosphere is defined as open channel flow. Open channel flow occurs in streams, rivers, canals, drainage channels, and roadside ditches as well as in conduits such as culverts and storm drains that are not flowing full. This section discusses open channel flow and presents criteria to be used for hydraulic design and evaluation of open channels, including roadside ditches. Any work in natural channels may be subject to the restrictions of Boulder County and FEMA floodplain regulations. Section 1400, Environmental and Regulatory Permitting discusses the permits that will be required for work in channels.

For a thorough discussion of open channel design principles, the user is encouraged to review the most recent version of the USDCM (UDFCD, 2016). Many other excellent references are available, including Chow (1959) and King and Brater (1963).

702 HYDRAULICS OF OPEN CHANNELS

The hydraulics of an open channel can be complex, ranging from steady state uniform flow to unsteady, rapidly varied flow. Most drainage design involves uniform, gradually varied, or rapidly varied flow states. Steady uniform flow occurs when the depth of flow remains constant. The calculations for both uniform and gradually varied flow are relatively simple and are based on the assumption of parallel streamlines. By contrast, rapidly varied flow calculations, which are used for things like hydraulic jumps and flow over spillways, have solutions that are generally empirical in nature. This section presents basic equations and computational procedures for uniform, gradually varied, and rapidly varied flow for hydraulic jumps and weirs.

702.1 Uniform Flow

Open channel flow is considered uniform if the depth of flow is the same at every section of the channel. For a given channel geometry, roughness, discharge, and slope, there is only one possible depth for maintaining uniform flow. This is called the normal depth. For a prismatic channel cross section, the water surface will be parallel to the channel bottom during uniform flow. Uniform flow rarely occurs in nature and is difficult to achieve, even in a laboratory. However, channels are designed by assuming uniform flow as an approximation that is adequate for planning purposes.

Calculations for normal flow depth shall be based on Manning's equation shown as Equation 700.1. A spreadsheet is an effective tool for quick analysis.

$$Q = \frac{1.49}{n} A^{5/3} P^{-2/3} \sqrt{S} = \frac{1.49}{n} A R^{2/3} \sqrt{S} \qquad (700.1)$$

where:

$Q =$ flow rate $\left(\text{ft}^3/\text{s}\right)$

$n =$ Manning roughness coefficient

$A =$ area $\left(\text{ft}^2\right)$

$P =$ wetted perimeter $\left(\text{ft}\right)$

$R =$ hydraulic radius = A/P $\left(\text{ft}\right)$

$S =$ slope of the energy grade line $\left(\text{ft/ft}\right)$.

For prismatic channels with uniform flow, the slope of the energy grade line (EGL), hydraulic grade line (HGL), and bottom of channel can be assumed to be equal. Table 700-1 provides recommended Manning roughness coefficients for various channel conditions. As the roughness increases, a given flow rate will have a greater depth and slower velocity. Conversely, a lesser roughness results in shallower depth and faster velocity. Selection of roughness coefficients for both the main channel and the overbanks is a critical part of the design and evaluation of an open channel.

Table 700-1. Manning Roughness Coefficients (modified from UDFCD, 2016)

Location and Cover	For Velocity, Froude Number, and Shear Stress Calculations	For Water Surface Elevation and Depth Calculations
Main Channel		
Sand or clay bed	0.03	0.04
Gravel or cobble bed	0.035	0.07
Troweled concrete	0.012	0.015
Vegetated Overbanks		
Turfgrass sod	0.03	0.04
Native grasses	0.032	0.05
Herbaceous wetlands (few to no willows)	0.06	0.12
Willow stands, woody shrubs	0.07	0.16

702.2 Critical Flow

Critical flow in an open channel is characterized by the following conditions:

1. The specific energy is at a minimum for a given discharge.
2. The discharge is at a maximum for a given specific energy.
3. The specific force is at a minimum for a given discharge.

4. The velocity head is equal to half the hydraulic depth in a channel with a minimal slope.
5. The Froude Number (Fr) is equal to 1.0.

When critical flow exists for uniform flow, the channel slope is at the critical slope. A slope flatter than critical will cause subcritical flow and result in a Froude number smaller than 1.0. A slope steeper than critical will cause supercritical flow and result in a Froude number larger than 1.0. When flow is at or near critical, it is unstable because minor changes in specific energy, such as from channel debris, will cause a major change in depth. The Equation 700.2, used to calculate the Froude Number, should be used to check flow state for all open channel designs.

$$Fr = \frac{v}{\sqrt{gD_h}} \tag{700.2}$$

where:

$Fr =$ Froude number $\left(\text{dimensionless}\right)$

$v =$ velocity $\left(\text{ft/s}\right)$

$g =$ gravitational acceleration $\left(32.2\ \text{ft/s}^2\right)$

$A =$ channel flow area $\left(\text{ft}^2\right)$

$T =$ top width of flow area $\left(\text{ft}\right)$

$D_h =$ hydraulic depth, $D_h = A/T$ $\left(\text{ft}\right)$.

702.3 Gradually Varied Flow

The most common occurrence of gradually varied flow in storm drainage design is the backwater created by culverts, inlets, and channel constrictions. For these conditions, flow depth will be greater than normal depth in the channel and the water surface profile must be computed using a backwater technique—either the direct step or the standard step method. The direct step method is best suited to the analysis of simple prismatic channels, whereas the standard step method is best suited for irregular or nonuniform cross-sections. The most general and widely used program is currently HEC-RAS, developed by the U.S. Army Corps of Engineers. HEC-RAS is recommended for calculating water surface profiles in Boulder County. If a designer would like to compute water surface profiles by hand, the methodology for using both the direct-step and standard-step methods can be found in the HEC-RAS *Hydraulic Reference Manual* (Brummer, 2010), as well as in *Open Channel Hydraulics* (Chow, 1959).

702.4 Rapidly Varied Flow

Rapidly varied flow is characterized by very pronounced curvature of the streamlines. The change in curvature may become so abrupt that the flow profile is virtually broken, resulting in a state of high turbulence. Several common instances of rapidly varied flow include weir flow, orifice flow, and hydraulic jumps. Only hydraulic jumps will be discussed in this section. In Boulder County, weir and orifice flow are used almost exclusively for detention pond outlets and will be discussed in Section 1200, Detention and Permanent Water Quality.

Hydraulic jumps may occur at grade control structures, inside storm drains or culverts, and at the outlet of a spillway and can be very erosive and affect hydraulic capacity. For grassed channels, the forces from a hydraulic jump must be controlled to prevent serious damage. Drops or other grade control structures can be used to direct the jump to an area specifically designed to resist the forces that come with it.

Jump locations within storm drain systems can be approximated by intersecting the energy grade line of the supercritical and subcritical flow reaches. Because storm drain velocity is limited to 16 feet per second, and because all storm drains in the county are required to be concrete, little threat of damage exists, but pipe capacity may be impacted. The effect on pipe capacity can be determined by evaluating the energy grade line and taking into account the energy lost by the jump. In general, for Froude Numbers less than 2.0, energy loss is less than 10 percent.

For long concrete boxes, the concerns of the jump are the same as for storm drains. However, the jump can be adequately defined for box conduits and for spillways using the jump characteristics of rectangular sections. A detailed evaluation of the hydraulic jump is beyond the scope of this MANUAL, but design procedures are provided in Chow (1959) and Peterska (1978). The UDFCD's USDCM also has procedures and calculations that can be used. Calculations must be included with the required submittals in accordance with Section 200.

703 OPEN CHANNEL DESIGN STANDARDS

The design standards for all open channels in the county, with the exception of roadside ditches, are the same as those in the most recent edition of the USDCM. The design process for an open channel can be somewhat circular because of a wide range of options available for materials, typical cross section, channel slope, and the prevalence of drop structures. The design components that have the greatest potential effect on the performance and cost of the improvements should be evaluated early on to guide the design process. Design considerations include allowable velocity, required capacity, curvature limitations, right-of-way constraints, structures such as bridges or culverts, maintenance access, access and safety of recreational users including boaters, and the desire for ecological components to be included in the design. Figure 700-1 shows an example of the typical natural stream in Boulder County.

The USDCM offers guidance on channel centerline and cross section layout, hydraulic analysis, and using rocks and boulders for protection from erosion. The USDCM also puts a considerable amount of emphasis on preserving and restoring natural stream corridors. Boulder County is a strong proponent of the use of ecological concepts to preserve and restore our local channels. Ecological channel design includes bioengineering practices that utilize vegetation in a combination with natural structural measures to stabilize and protect stream banks while providing habitat for a number of species. Master plans often specify where ecological treatments have already been approved for use and are expected to be constructed.

Ecological design can have numerous public and environmental benefits when applied in an appropriate location, but care should be taken in selecting the location and completing the design calculations to ensure an ecological design will hold up under the stream forces it is intended to withstand. Numerous types of bioengineering components can be used in Boulder County. General schematic details of the bioengineering components that have been approved for use by the county are included as an appendix to this MANUAL. Table 700-2 lists some of the potential advantages and disadvantages to using an ecological channel design, as opposed to the more traditional riprap and concrete design concepts. Boulder County is a strong proponent of using ecological design concepts to restore channels damaged by flood events, with particular emphasis on reaches where riparian vegetation was destroyed. The potential for every channel restoration project to include ecological components shall be examined and discussed with the county.

Figure 700-1. Typical Natural Stream (Boulder County, 2016).

Table 700-2. Ecological Treatment Advantages and Disadvantages

Advantages	Disadvantages
Environmental clearances (may facilitate permits)	Potentially more expensive
Aesthetically pleasing	Specialized vegetation
Fish passage	Additional maintenance required
Habitat for fish, birds, and macroinvertebrates	Susceptible to failure during larger storms
Open space creation and preservation	May require a larger footprint
Water temperature moderation	Specific hydrologic conditions required
Water quality enhancement	

Ecological channel design may be applied when the overall channel design is firmly rooted in engineering principles and when the following conditions are met:

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

It is important to note that bioengineered elements are commonly designed to withstand flows from more frequently occurring storms. Design events are typically between the 1.5-year to 10-year storm, with the 100-year storm occasionally being a consideration. While designing for a larger event is prudent, stability during such events may often be achieved by traditional engineering techniques because bioengineered elements may not remain stable above a certain threshold. If stability is critical at a given location, such as at bridge piers or near a structure, bioengineering measures may not provide sufficient stability on their own, without the addition of traditional engineering techniques. Bioengineering techniques can be incorporated into almost all traditional engineering projects, often to great ecological benefit. The design approach must balance ecological function with the need for channel stability when selecting a design discharge. If a channel segment is expected to withstand the 100-year event, it needs to be designed to meet that criterion, regardless of the techniques used. Both the county and the design engineer should discuss and agree upon the various ecological and hydraulic criteria the design will meet.

The key elements to consider in an ecological channel design include hydrology, hydraulics, geomorphology, physiochemistry, and biology. Each of the following elements should be addressed when designing the channel.

1. Future hydrologic changes associated with urbanization
2. Channel Stability
3. Hydrology to support vegetation
4. Supplemental structural measures.

The USDCM should be reviewed as part of the design process because it offers valuable guidance on typical minimum standards. The Natural Channel Design Review Checklist published by the US Fish and Wildlife Service should also be reviewed to ensure that all appropriate parameters have been considered.

No specific criteria or design guidance is included in this MANUAL because each site is unique and will require a solution based on the goals for each site. However, there are publications that offer guidance on ecological channel design, and these should be consulted to ensure the design will stand up to the chosen design hydraulic event. The Technical Supplements contained in *Stream Restoration Design* (National Engineering Handbook 654) (NRCS, 2007), offer extensive and detailed guidance on physical design of ecological channels. Specifically, Technical Supplements 14I through 14O offer design guidance and equations for soil bioengineering, using large woody material for habitat and bank protection, vegetated rock walls, fish passage, and fish lunkers, among many other components.

Monitoring and maintenance should be performed throughout the life of the ecological channel design. The following list consists of four periods when a bioengineered structure is most at risk:

1. Immediately after construction
2. During the driest time of the year
3. During high magnitude discharge events
4. When a shift in plant community occurs away from plants chosen for biostabilization.

To achieve the highest likelihood of establishment of the specified vegetation, a 3-year maintenance plan from a certified landscaping company that understands native vegetation will be required. If seed is used, Boulder County Parks and Open Space shall be consulted to provide a site-specific seeding mix for each project. Plantings need to be completed in the fall or late winter to provide the best odds of establishment. Depending on the site, irrigation may also be required. Other techniques to improve the odds of successful vegetation establishment include the following:

1. Pretreating the project site to remove invasive or noxious species
2. Selecting an appropriate and diverse early-seral seed mix with the potential to fully occupy the site's botanical niches
3. Adequate seeding rate and seeding techniques coupled with soil amendments as determined by proper soil testing
4. Minimizing or eliminating the use of nitrogen, because exotic weeds are often preferentially stimulated over native species
5. Monitoring the nontarget species and noxious weed seeds that are often present in a seed mix
6. Developing an iterative weed management plan based on regularly scheduled monitoring.

704 ROADSIDE DITCH DESIGN STANDARDS

Much like the design of any open channel, design of roadside ditches is a balance of several design components, including velocity, capacity, available right-of-way, slope, and cross-sectional geometry. A wide range of roadside ditch geometry is allowed in the county. Section 900, Roadways, discusses several constraints and factors to consider when laying out a roadside ditch. The capacity requirements of a roadside ditch are based on roadway encroachment, also discussed in Section 900.

This section discusses permissible velocities and Froude numbers when designing a roadside ditch. Roadside ditch hydraulic calculations will be completed using Manning's equation. The Manning's roughness coefficients for calculating velocity, Froude number, and shear stress included in Table 700-1 will be used for all roadside dich calculations, including capacity and water surface elevation. The designer should note that if a ditch is expected to be vegetated, there is a much higher potential for erosion until vegetation is complete. The use of erosion control measures prior to revegetation will minimize this potential.

Roadside ditch flow with depths less than or equal to 1.0 feet have no Froude number or velocity limitations. For ditch flow depths greater than 1.0 feet, velocity shall not exceed 7.0 feet per second, and the Froude number shall not exceed 0.8. These criteria are shown in Table 700-3.

Table 700-3. Allowable Velocity and Froude Number for Roadside Ditches

Design Component	Maximum Allowable Values	
	Flow Depth ≤ 1.0 feet	Flow Depth > 1.0 feet
Velocity	No maximum	7 fps
Froude Number	No maximum	0.8

Where roadway slopes are steep enough to result in ditch slopes that are too steep for ditch velocities or Froude numbers to meet criteria, a flattened ditch slope may be used with ditch checks placed at intervals to make up for grade discrepancies. An example of a ditch check is in Section 1100, Hydraulic Structures.

705 REFERENCES

Brummer, G., 2010. *HEC-RAS River Analysis System Hydraulic Reference Manual*, prepared by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC), Davis, CA.

Chow, V. T., 1959. *Open Channel Hydraulics*, McGraw-Hill College, Burr Ridge, IL.

King, H. W. and E. F. Brater, 1963. *Handbook of Hydraulics for the Solution of Hydrostatic and Fluid-Flow Problems*, McGraw-Hill, New York, NY.

Natural Resources Conservation Service, 2007. *Part 654 National Engineering Handbook Stream Restoration Design*, prepared by the Natural Resources Conservation Service, Washington, DC.

Peterska, A. J., 1978. “Hydraulic Design of Stilling Basins and Energy Dissipators,” Engineering Monograph No. 25, U.S. Department of the Interior, U.S. Bureau of Reclamation, Washington, DC.

Urban Drainage and Flood Control District, 2016. *Urban Storm Drainage Criteria Manual: Volume 1 Management, Hydrology, and Hydraulics*, prepared by the Urban Drainage and Flood Control District, Denver, CO.